

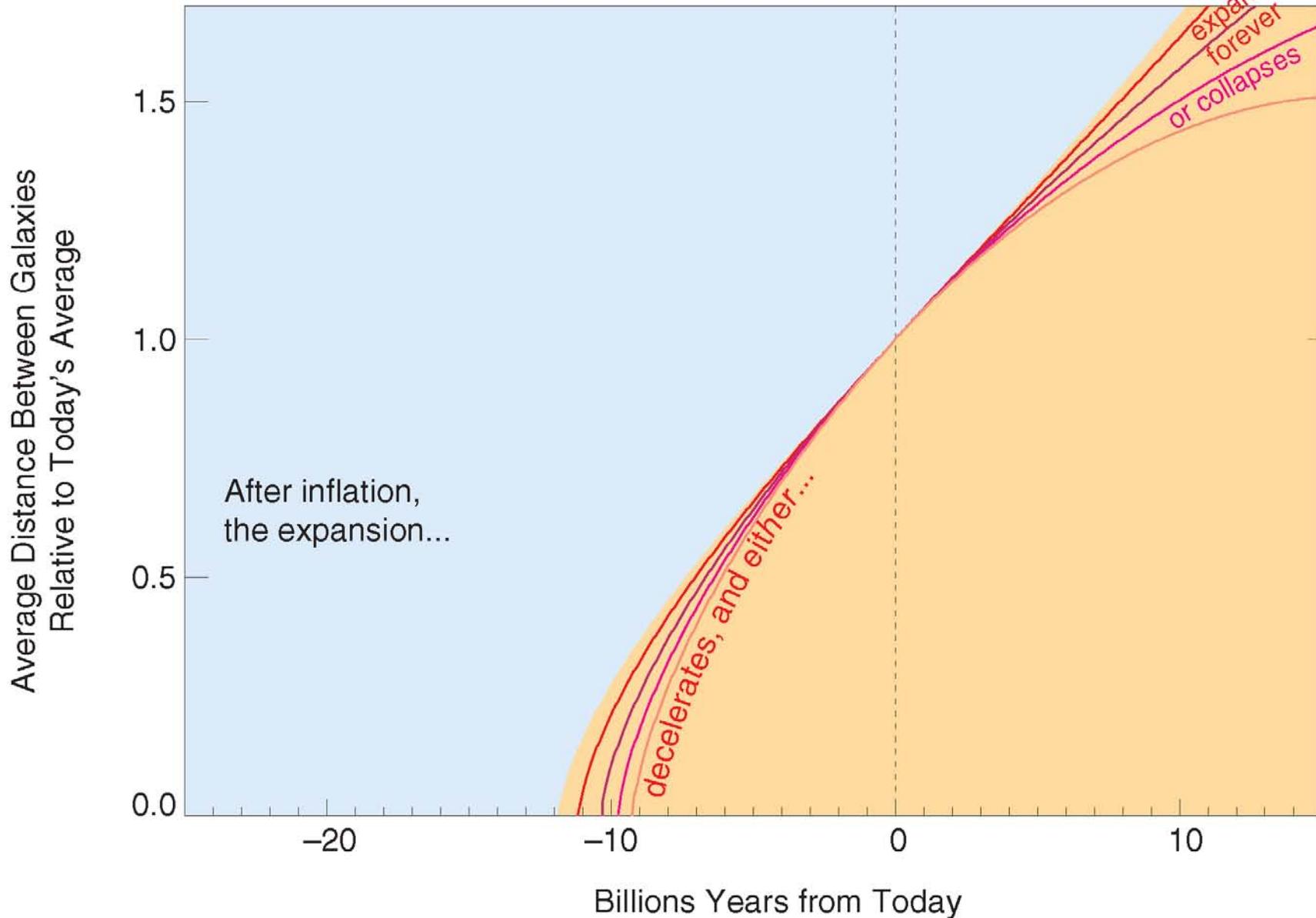
# Supernovae and a 2.4-m WFIRST

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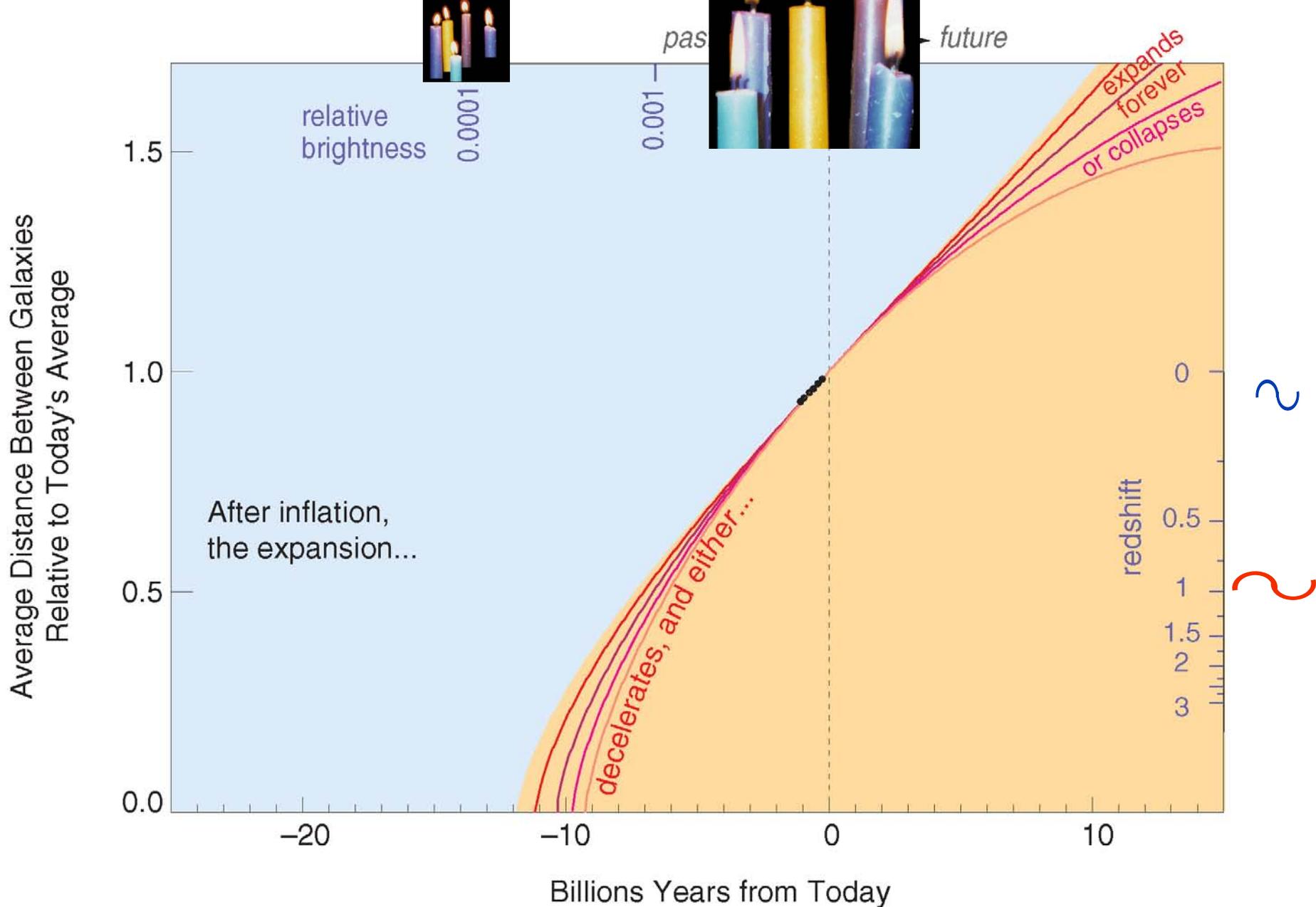
# Expansion History of the Universe

Perlmutter, Physics Today (2003)

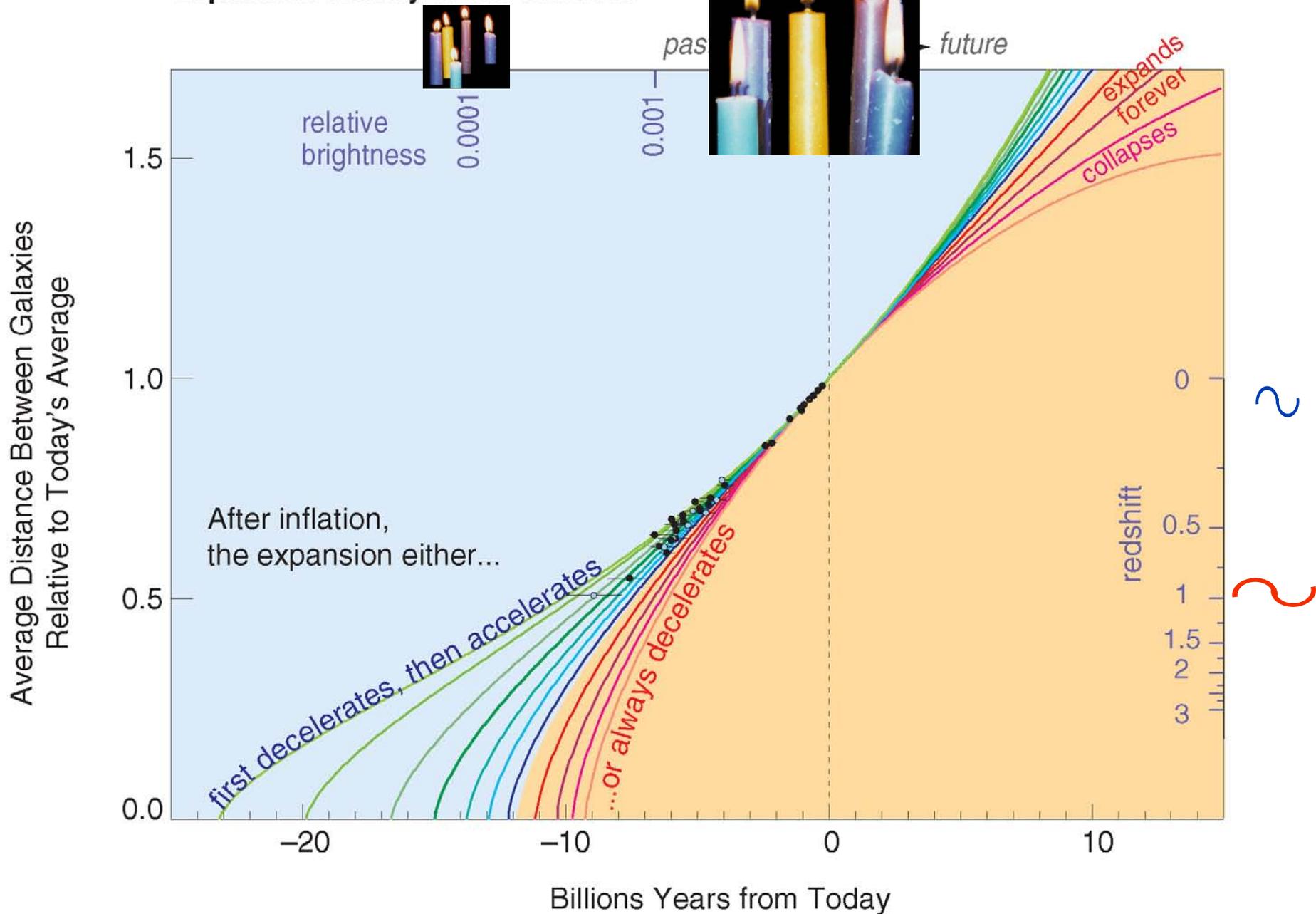
past ← today → future



# Expansion History of the Universe

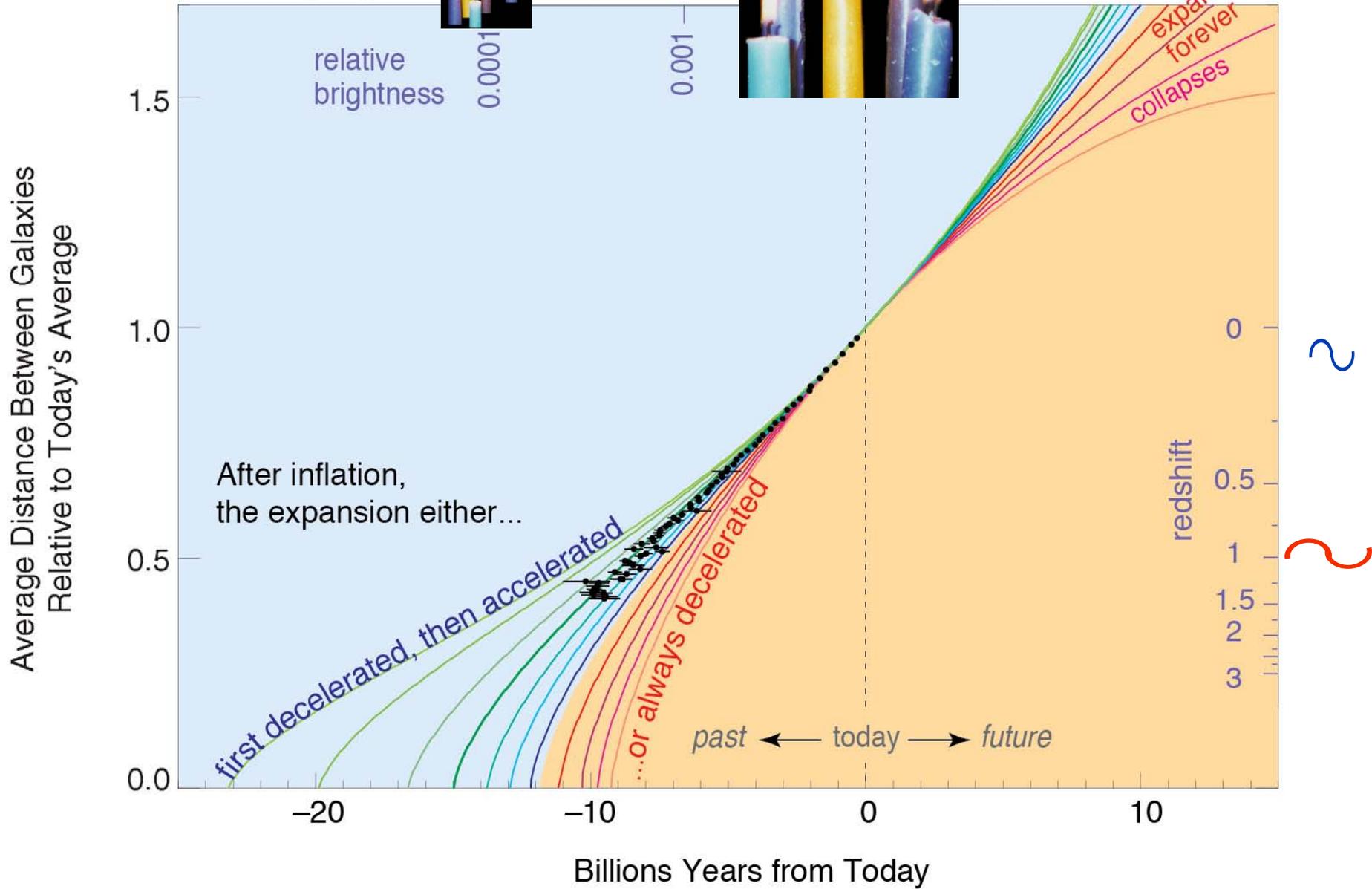


# Expansion History of the Universe



# Expansion History of the Universe

Perlmutter, Physics Today (2003) + Union (2011)



Average Distance Between Galaxies  
Relative to Today's Average

After inflation,  
the expansion either...

first decelerated, then accelerated

...or always decelerated

expands  
forever

collapses

past ← today → future

redshift



# Design Surveys for DRM 1 and DRM 2

Assume 6 months for Supernova Survey

## DRM 1

- 1.3 m mirror
- Imager with
  - 36 H2RG detectors
  - 0.18 "/pixl
  - 0.36 sq degrees
- Filter wheel with
  - 4 filters
  - R=75 Prism
- 2.5 micron  $\lambda$  cutoff

## DRM 2

- 1.1 m mirror
- Imager with
  - 14 H4RG detectors
  - 0.18 "/pixl
  - 0.56 sq degrees
- Filter Wheel with
  - 4 filters
  - R=75 Prism
- 2.5 micron  $\lambda$  cutoff

# WFIRST DRM A – Dave Constants Baseline

Assume 6 months for Supernova Survey

## DRM A

- 2.4 m on axis mirror
- Imager with
  - 18 H4RG detectors (6x3)
  - 0.11 "/pixl
  - 0.28 sq degrees
- Filter wheel with
  - 4 filters
  - R=75 Prism spectr.
- 2.0 micron  $\lambda$  cutoff

# Assume 4 Filter Bands

$$\Delta \lambda = \lambda / 4.5$$

Filter	$\lambda$ Central	$\Delta \lambda$	$\lambda$ Range
1	1.15	0.26	1.02 – 1.28
2	1.45	0.32	1.29 – 1.61
3	1.80	0.40	1.60 – 2.00
4	2.25	0.50	2.00 – 2.50

These were the four filter bands for DRM1 and 2.

We planned on using bands 2,3,4 with the 2.5 micron cutoff.

For DRM A with a 2.0 micron cutoff we plan on using bands 1,2,3.

We will fine tune these when the filter bands for DRM A are chosen.

## Supernova Signal - counts/sec/Filter Band

- The supernova signal in the three filters was calculated by Alex Kim by transforming the observer frame filter bands to the supernova rest frame and evaluating the flux in these rest frame bands.

- | <u>Z</u> | <u>Band1</u> | <u>Band2</u> | <u>Band3</u> | <u>Band4</u> |
|----------|--------------|--------------|--------------|--------------|
| 0.15     | 23.096       | 17.614       | 10.814       | 4.814        |
| 0.25     | 11.096       | 7.726        | 5.843        | 2.093        |
| 0.35     | 6.087        | 4.624        | 3.778        | 0.977        |
| 0.45     | 3.749        | 3.348        | 2.644        | 1.323        |
| 0.55     | 3.044        | 2.557        | 1.829        | 1.337        |
| 0.65     | 2.615        | 1.957        | 1.414        | 1.249        |
| 0.75     | 2.387        | 1.461        | 1.181        | 1.140        |
| 0.85     | 2.088        | 1.134        | 1.086        | 1.032        |
| 0.95     | 1.707        | 1.080        | 0.916        | 0.870        |
| 1.05     | 1.452        | 1.046        | 0.793        | 1.099        |
| 1.15     | 1.193        | 0.982        | 0.658        | 0.942        |
| 1.25     | 1.061        | 0.949        | 0.555        | 1.018        |
| 1.35     | 0.954        | 0.885        | 0.497        | 1.068        |
| 1.45     | 0.864        | 0.778        | 0.510        | 1.060        |
| 1.55     | 0.840        | 0.701        | 0.510        | 1.282        |
| 1.65     | 0.795        | 0.632        | 0.490        | 0.843        |

For a 1.3 m dia  
unobstructed view mirror

Adjusted for 75%  
telescope thruput

## Supernova Signal - counts/sec/Filter Band

- The supernova signal in the three filters was calculated by transforming the observer frame filter bands to the supernova rest frame and evaluating the flux in these rest frame bands.

<u>Z</u>	<u>Band1</u>	<u>Band2</u>	<u>Band3</u>	<u>Band4</u>
• 0.15	61.398	46.826	28.748	
• 0.25	29.284	20.538	15.535	
• 0.35	16.183	12.292	10.043	
• 0.45	9.966	8.901	7.029	
• 0.55	8.088	6.798	4.863	
• 0.65	6.951	5.204	3.760	
• 0.75	6.345	3.885	3.140	
• 0.85	5.552	3.015	2.887	
• 0.95	4.536	2.871	2.435	
• 1.05	3.859	2.782	2.108	
• 1.15	3.170	2.610	1.750	
• 1.25	2.819	2.522	1.476	
• 1.35	2.536	2.353	1.321	
• 1.45	2.297	2.069	1.355	
• 1.55	2.233	1.864	1.357	
• 1.65	2.115	1.680	1.302	
•				

For a 2.4 m dia  
obstructed view mirror

Adjusted for 75%  
telescope thruput

Wavelengths < 2.0  $\mu$

## Calculation of Exposure Times

- Exposure times  $t$  in each of the filter bands for a  $S/N=15$  in each band
- $t = [(S/N)/s]^2 [s + n_{\text{pix}} (Z+D+r^2/t)]$  sec
- $n_{\text{pix}}$  = no of pixels in image
- $S/N = 15$  required signal to noise
- $s$  is SNe signal in counts/sec/band
- $Z$  is the Zodi bckgrd in cts/sec/pix
- $D$  is the dark current in cts/sec/pix
- $r$  is the read noise (assume single read here, should change with multiple exposures per point)

## Calculation of the Zodi Background

- Zodiacal light background from paper by Greg Aldering
  - $\log_{10} f(\lambda) = -17.755 - 0.73(\lambda - 0.61)$  ergs/cm<sup>2</sup>/sec/Å/arcsec<sup>2</sup>
- Converting this to more relevant units
  - $f(\lambda) = 2.47 \cdot 10^{-2} \lambda e^{-1.68\lambda}$  photons/cm<sup>2</sup>/sec/μ/arcsec<sup>2</sup>
- Calculating counts/pixel/sec
  - $Z = f(\lambda) A_{\text{tel}} A_{\text{pixel}} \Delta\lambda$  counts/pixel/sec
  - Where  $A_{\text{tel}}$  is the Telescope area in cm<sup>2</sup>
  - $A_{\text{pixel}}$  is the area of a pixel in arcsec<sup>2</sup>
  - $\Delta\lambda$  is the wavelength range contributing

# Parameters used in the Exposure Time Calculations

Using Calculated Signal/Filter Band (counts/sec/filter band)

Parameter	Imaging	Slitless Spectra	IFU Spectra
Signal to noise $S/N$	15	15	15
No of pixels $npix$	12.6	133.3	88
Zodi Bkgrd $Z$	As calculated		
Dark Current $D$	0.015 e/pixel/sec	0.015	0.010
Read noise $r$	10.0 e	10.0	5.0
Pixel area $A_{pix}$	$(0.11)**2$	$(0.11)**2$	$(0.11)**2$
Wavelength $\lambda$	Center of band		
Range admitted $\Delta\lambda$ in zodi backgrd	Width of filter band	0.6 to 2.0 = 1.4 $\mu$	< 0.02 $\mu$
Spectrometer Res		R = 75 (150/pix)	R = 50 (100/pix)

# Imaging Exposure times

- | Z    | Band1 | Band2 | Band3 |
|------|-------|-------|-------|
| 0.15 | 10.9  | 14.3  | 23.5  |
| 0.25 | 23.1  | 33.4  | 44.4  |
| 0.35 | 42.9  | 57.4  | 70.5  |
| 0.45 | 72.2  | 81.4  | 103.9 |
| 0.55 | 90.8  | 109.7 | 157.4 |
| 0.65 | 107.6 | 148.9 | 212.6 |
| 0.75 | 119.3 | 210.6 | 264.3 |
| 0.85 | 139.0 | 288.3 | 293.1 |
| 0.95 | 176.3 | 306.8 | 363.5 |
| 1.05 | 214.1 | 319.4 | 438.5 |
| 1.15 | 273.4 | 347.0 | 563.0 |
| 1.25 | 317.6 | 362.8 | 714.4 |
| 1.35 | 364.6 | 397.7 | 838.1 |
| 1.45 | 415.9 | 472.9 | 807.4 |
| 1.55 | 432.3 | 546.1 | 805.8 |
| 1.65 | 465.4 | 632.6 | 856.4 |

Exposure times in each of the filter Bands for a S/N=15 in each band for a 2.4 m mirror

Calculated exposure times as:

$$t = [(S/N)/s]^2 [s + n_{\text{pix}} (Z+D+r^2/t)] \text{ sec}$$

$n_{\text{pix}}$  = no of pixels in image

$S/N = 15$  required signal to noise

$s$  is SNe signal in counts/sec/band

$Z$  is the Zodi bckgrd in cts/sec/pix

$D$  is the dark current in cts/sec/pix

$r$  is the read noise (assume single read here, should change with multiple exposures per point)

## Calculation of the slitless and IFU exposure times to get S/N=15 in Filter Bands 1,2,3

<u>Z</u>	<u>IFU</u>			<u>Z</u>	<u>Slitless</u>		
0.15	10.29	13.55	22.34	0.15	40.06	57.16	114.84
0.25	21.92	31.66	42.44	0.25	111.67	195.13	312.49
0.35	40.65	54.44	67.70	0.35	291.20	472.70	683.69
0.45	68.27	77.25	100.40	0.45	693.48	856.06	1338.58
0.55	85.86	104.25	153.20	0.55	1025.13	1427.05	2727.36
0.65	101.67	141.56	208.48	0.65	1367.65	2391.02	4515.19
0.75	112.71	200.30	260.66	0.75	1629.11	4232.95	6439.53
0.85	131.31	274.42	289.95	0.85	2108.14	6978.31	7600.60
0.95	166.36	292.01	361.93	0.95	3125.60	7684.18	10652.03
1.05	201.96	304.11	439.34	1.05	4289.56	8179.68	14183.98
1.15	257.59	330.37	568.98	1.15	6320.96	9282.46	20522.72
1.25	299.00	345.52	728.24	1.25	7969.42	9934.07	28817.69
1.35	342.98	378.83	859.24	1.35	9824.05	11403.05	35934.87
1.45	391.01	450.60	826.68	1.45	11951.81	14715.55	34145.42
1.55	406.35	520.53	824.91	1.55	12651.35	18101.53	34048.58
1.65	437.27	603.27	878.60	1.65	14086.77	22268.28	37004.04

## Measurements Errors on each Supernova

- Estimate that we need a  $S/N = 15$  in each of 3 bands to get a measurement error of 12% for each supernova
- The actual exposure times we propose to use may not be as long as the times we have calculated as to get  $S/N=15$  or 12 % measurement error for each supernova.
- Estimate actual measurement error as

$$\sigma_{\text{meas}} = (12 \%) \times \text{Sqrt}(\text{time for 12\%} / \text{actual exp time})$$

- Assign this error for each supernova

## Supernova Intrinsic spread

- Use intrinsic supernova spread in peak flux as we agreed:
  - Rest frame B band 16 %
  - Rest frame Z band 15 %
  - Rest frame J band 13 %
  - Rest frame H band 12 %

- With a  $2.5\mu$  the reddest band is  $2.0$  to  $2.5\mu$ , so this wavelength dependence translates into a  $z$  dependence

$$\sigma_{\text{intrinsic}} = 0.10 + 0.033 z$$

- With the  $2.0\mu$  cutoff the reddest band is  $1.6$  to  $2.0\mu$ , and the wavelength dependence translates to

- $\sigma_{\text{intrinsic}} = 0.11 + 0.033 z$

## Error Model Used

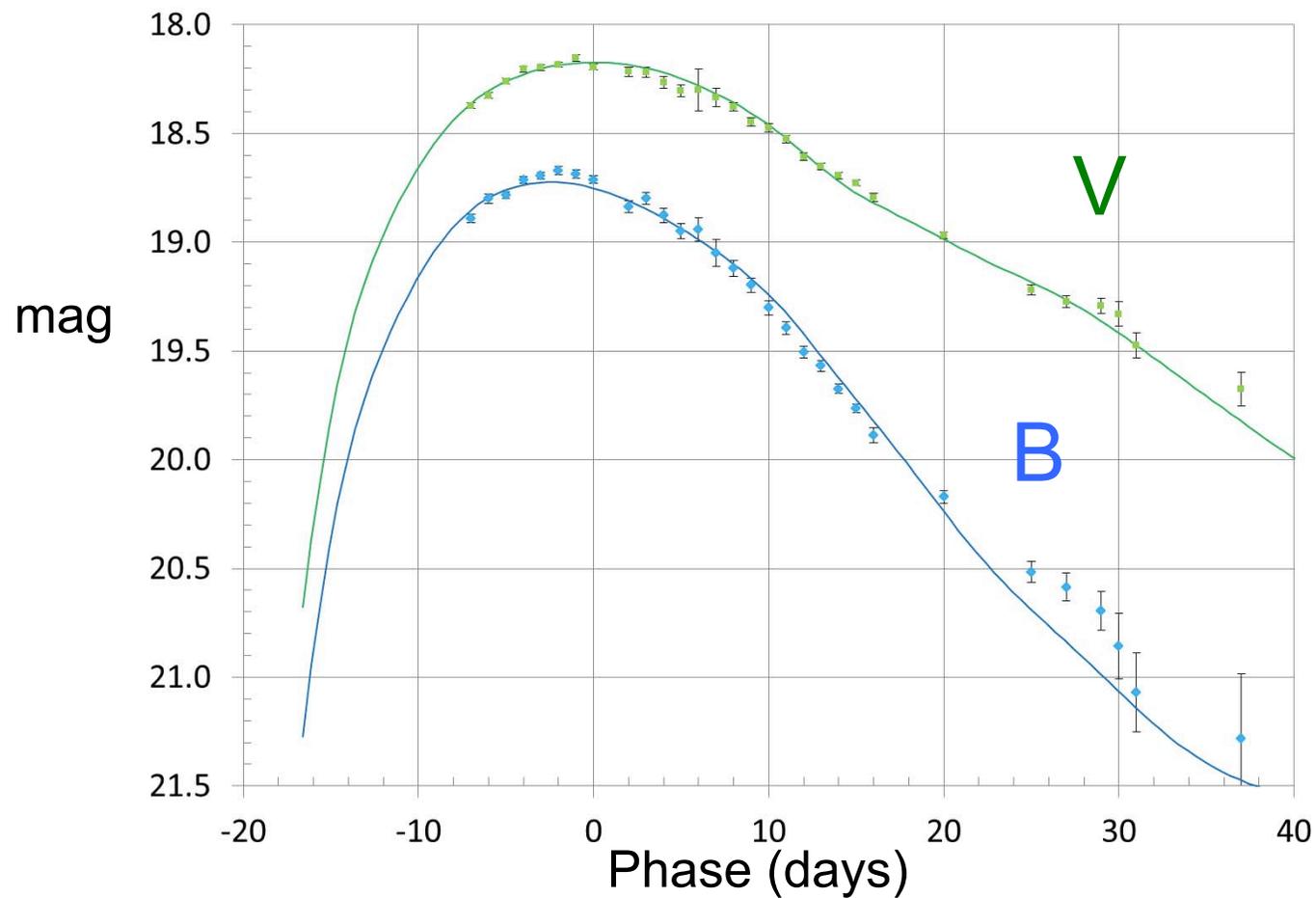
- Use the program by Eric Linder to calculate Figures of Merit
- Statistical errors i.e. errors that are reduced by  $1/\sqrt{N}$ 
  - For the intrinsic spread use  $\sigma_{\text{int}} = 0.11 + 0.33z$
  - measurement errors per supernova that varies with z bin
  - Add these in quadrature and divide by  $\sqrt{N(z)}$  to get  $\sigma_{\text{stat}}$
- Systematic ( error as suggested by Adam Riess)  
 $\sigma_{\text{sys}} = 0.02 [ 1.0\mu / \{ \lambda_0 / (1+z) \} ]$   
where  $\lambda_0$  is the center of the reddest filter,  $1.8\mu$  in our case.
- Add these in quadrature  $\sigma_{\text{tot}} = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2}$

## Survey Cadence

- Plan to run supernova survey for 6 months spread over 1.8 years calendar time.
- Plan on supernova survey with a 5 day cadence, 33 hours per visit
- $(657/5)*33 \text{ hrs}/24 = 182 \text{ days} = 6 \text{ months}$

# SALT2 fits to LSQ11ot

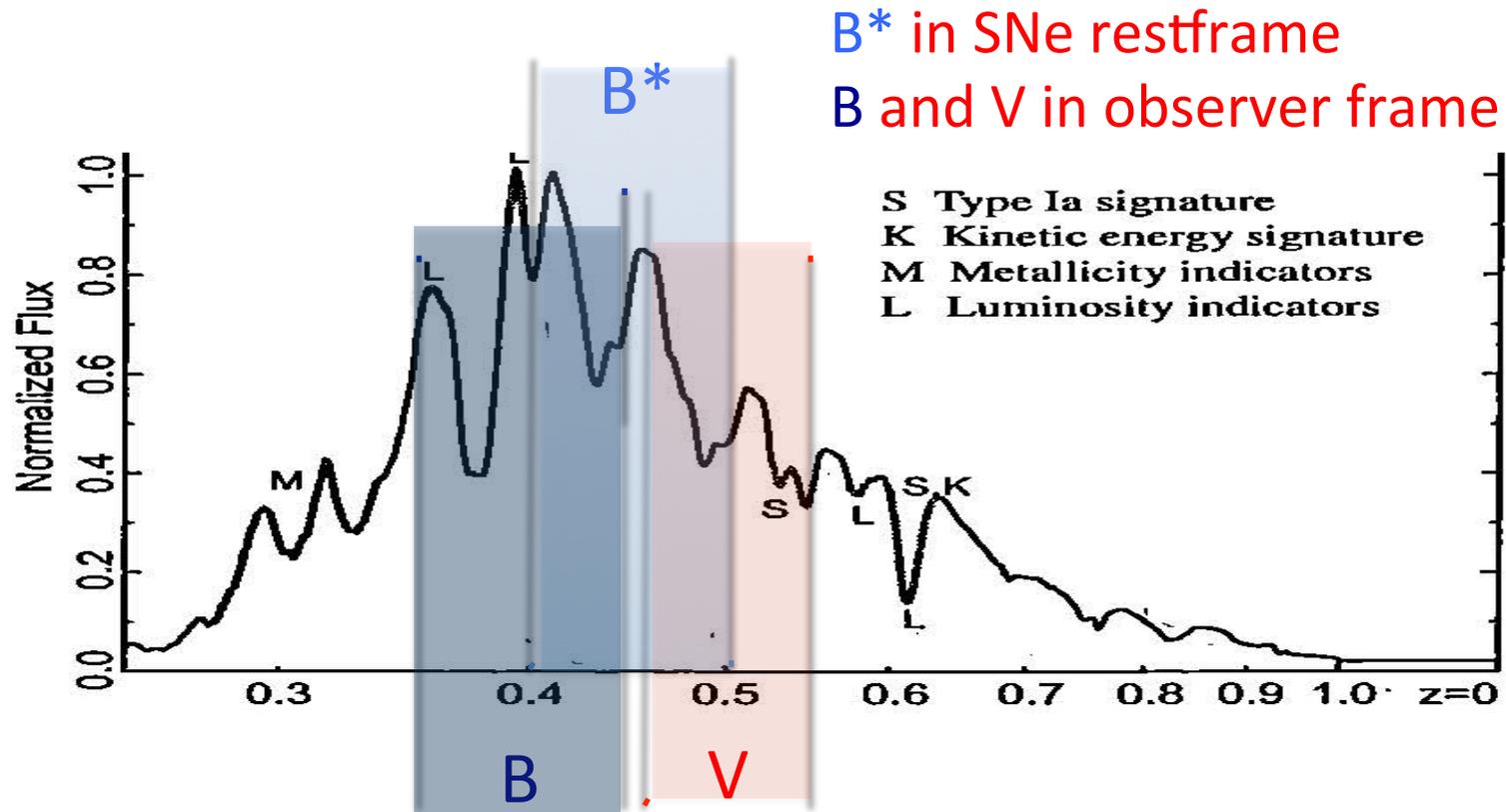
Lightcurves for a LaSilla/QUEST supernova from the SWOPE 1 m telescope at Las Campanas



## Systematic Errors

- The control of systematic errors is very important in the supernova survey. The main dependence of the systematic errors is on the method of measuring the lightcurves.
- Lightcurves from imaging in 3 filters
  - This method has the poorest systematics(K corrections, evolution and color systematics)
- Lightcurves from slitless prism spectrometer
  - Medium systematic errors(no K corrections, but still have evolution and color systematics, diversity of Type 1a subclasses)
- Lightcurves from IFU spectrometer with an additional high S/N spectrum near peak
  - This method has the best control of the systematic errors

# K corrections



Need knowledge of the spectrum to calculate rest frame B band from observer frame filter bands. Three filters are not a lot for the huge redshift range of 0.1 to 1.7.

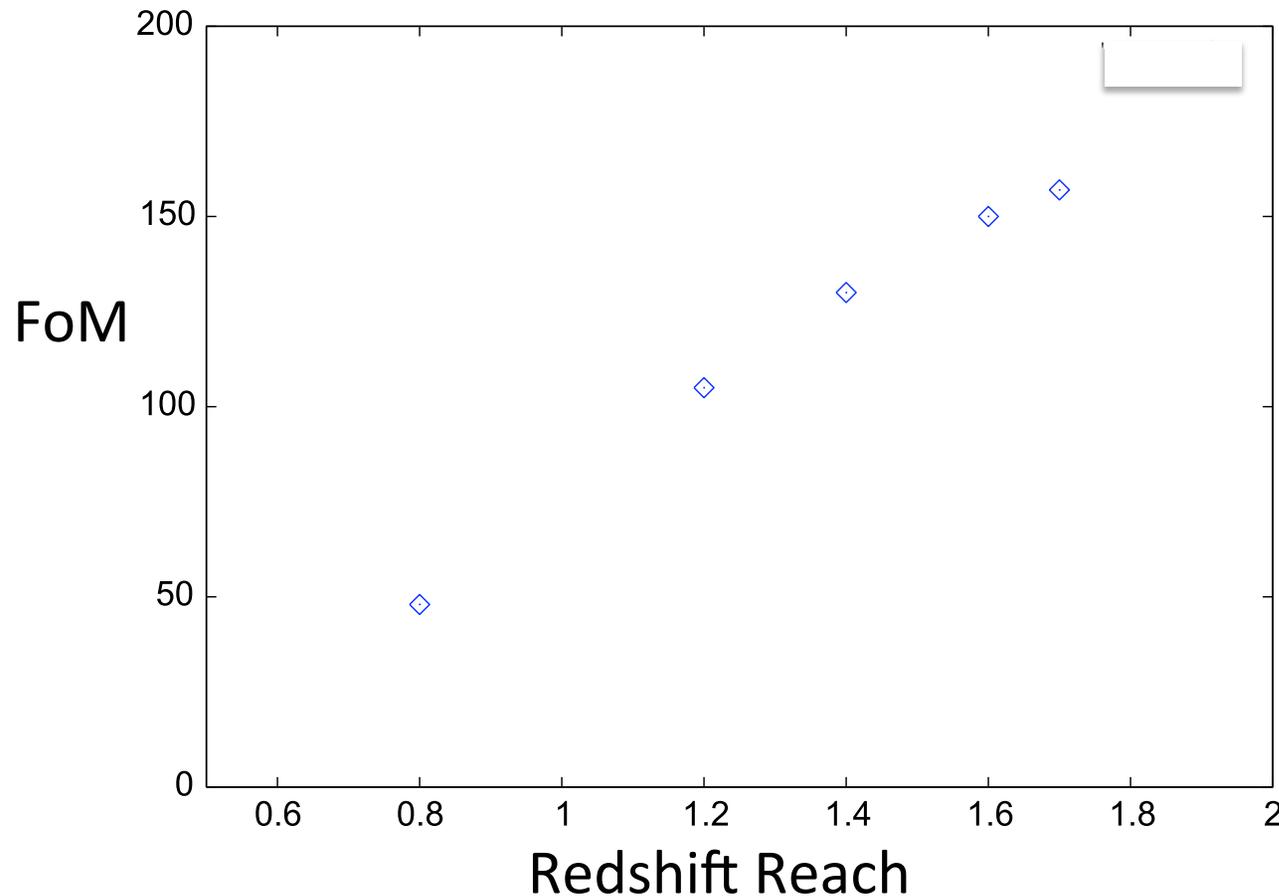
## Calculated for three survey Strategies

Method	Supernova Discovery	Confirm Type 1a Measure redshift	Lightcurves
A	Imager	Slitless Spectrometer	Imager
B	Slitless Prism Spectrometer	Slitless Spectrometer	Slitless Spectra
C	Imager	IFU Spectrometer	IFU Spectra

For each of these we used a redshift reach of  $z_{\max} = 1.7$

## DRM1 Figure of Merit vs Redshift Reach

Slitless Prism Spectroscopy, Lightcurves from imaging in 3 filters  
Tradeoff between lower z reach with more supernovae  
vs higher z reach with fewer supernovae  
in the same 6 month survey



# Realistic Error Assignments

With the 2.4 m on-axis Telescope,  $Z_{\max} = 1.7$

Survey	Systematic error	Intrinsic spread	FoM
A. Slitless, imaging lightcurves	$0.020(1+z)/1.8$	$0.11+0.033z$	180
B. Slitless, spectro lightcurves	$0.016(1+z)/1.8$	$0.11+0.033z$	197
C. IFU Deep, spectro lightcurves	$0.010(1+z)/1.8$	0.09	303

These Figures of Merit assume a sample of 800 ground based low redshift supernovae and use the Planck priors but do not include Stage III priors

# Slitless Spectrometer, Lightcurves from imaging

Use imaging to discover supernovae and get points on the lightcurve in 3 filters with S/N=15 in each

Use slitless prism spectrometer to type supernovae using the Silicon absorption feature and to get redshifts.  
S/N=0.7 per pixel

Time allocation during each 33 hour visit:

Obs mode	Low z $z < 0.8$			High z $z < 1.7$			Hours per visit
	Area	Exp time	hours/visit	Area	Exp time	hours/visit	
Imaging	14.0	100	4.2	5.04	500	7.5	11.7
Spectroscopy	14.0	650	9.0	5.04	2500	12.3	21.3

# A. 2.4m Slitless, Imaging Lightcurves FoM = 180

Z	No	S/N	No	S/N		Total	$\sigma_{sta}$	$\sigma/\sqrt{N}$	$\sigma_{sys}$	$\sigma_{total}$	
0.15	22	9.80	8	18.84	0	0.38	30	0.117	0.021	0.013	0.025
0.25	68	5.93	24	11.39	0	0.23	92	0.124	0.013	0.014	0.019
0.35	131	3.96	47	7.60	0	0.16	178	0.132	0.010	0.015	0.018
0.45	219	2.83	79	5.44	0	0.11	299	0.142	0.008	0.016	0.018
0.55	322	2.16	115	4.15	0	0.08	437	0.152	0.007	0.017	0.019
0.65	426	1.73	153	3.32	0	0.07	579	0.163	0.007	0.018	0.020
0.75	530	1.43	191	2.75	0	0.06	721	0.174	0.006	0.019	0.020
0.85	0	1.23	235	2.36	0	0.05	235	0.156	0.010	0.021	0.023
0.95	0	1.08	271	2.08	0	0.04	271	0.163	0.010	0.022	0.024
1.05	0	0.97	299	1.86	0	0.04	299	0.169	0.010	0.023	0.025
1.15	0	0.84	313	1.61	0	0.03	313	0.177	0.010	0.024	0.026
1.25	0	0.75	315	1.43	0	0.03	315	0.184	0.010	0.025	0.027
1.35	0	0.68	306	1.30	0	0.03	306	0.192	0.011	0.026	0.028
1.45	0	0.64	284	1.24	0	0.03	284	0.197	0.012	0.027	0.030
1.55	0	0.62	254	1.19	0	0.02	254	0.202	0.013	0.028	0.031
1.65	0	0.58	223	1.12	0	0.02	223	0.208	0.014	0.029	0.033

# Slitless Spectrometer, Lightcurves from Spectra

Use the slitless prism spectrometer to discover supernovae and get points on the lightcurve and redshift measurements  
With S/N=15 per synthetic band

Need modest imaging to locate objects

Time allocation for each 33 hour visit:

Obs mode	<u>Low z z&lt;0.8</u>			<u>High z z&lt; 1.7</u>			Hours per visit
	Area	Exp time	hours/visit	Area	Exp time	hours/visit	
Imaging	14.0	75	1	5.04	360	2	3
Spectroscopy	14.0	800	11	5.04	3800	19	30

## B. 2.4m Slitless, Spectro Lightcurves FoM = 197

Z	No	S/N	No	S/N		Total	$\sigma_{sta}$	$\sigma/\sqrt{N}$	$\sigma_{sys}$	$\sigma_{total}$	
0.15	22	8.96	8	20.03	0	0.32	30	0.119	0.021	0.010	0.024
0.25	68	5.22	24	11.68	0	0.18	92	0.129	0.013	0.011	0.017
0.35	131	3.39	47	7.59	0	0.12	178	0.145	0.011	0.012	0.016
0.45	219	2.39	79	5.35	0	0.08	299	0.166	0.010	0.013	0.016
0.55	322	1.81	115	4.04	0	0.06	437	0.190	0.009	0.014	0.016
0.65	426	1.44	153	3.22	0	0.05	579	0.216	0.009	0.015	0.017
0.75	530	1.19	191	2.65	0	0.04	721	0.245	0.009	0.016	0.018
0.85	0	1.02	235	2.28	0	0.04	235	0.195	0.013	0.016	0.021
0.95	0	0.89	271	2.00	0	0.03	271	0.211	0.013	0.017	0.022
1.05	0	0.80	299	1.79	0	0.03	299	0.226	0.013	0.018	0.022
1.15	0	0.69	313	1.54	0	0.02	313	0.250	0.014	0.019	0.024
1.25	0	0.61	315	1.37	0	0.02	315	0.273	0.015	0.020	0.025
1.35	0	0.56	306	1.25	0	0.02	306	0.294	0.017	0.021	0.027
1.45	0	0.53	284	1.19	0	0.02	284	0.307	0.018	0.022	0.028
1.55	0	0.51	254	1.14	0	0.02	254	0.317	0.020	0.023	0.030
1.65	0	0.48	223	1.07	0	0.02	223	0.335	0.022	0.024	0.032

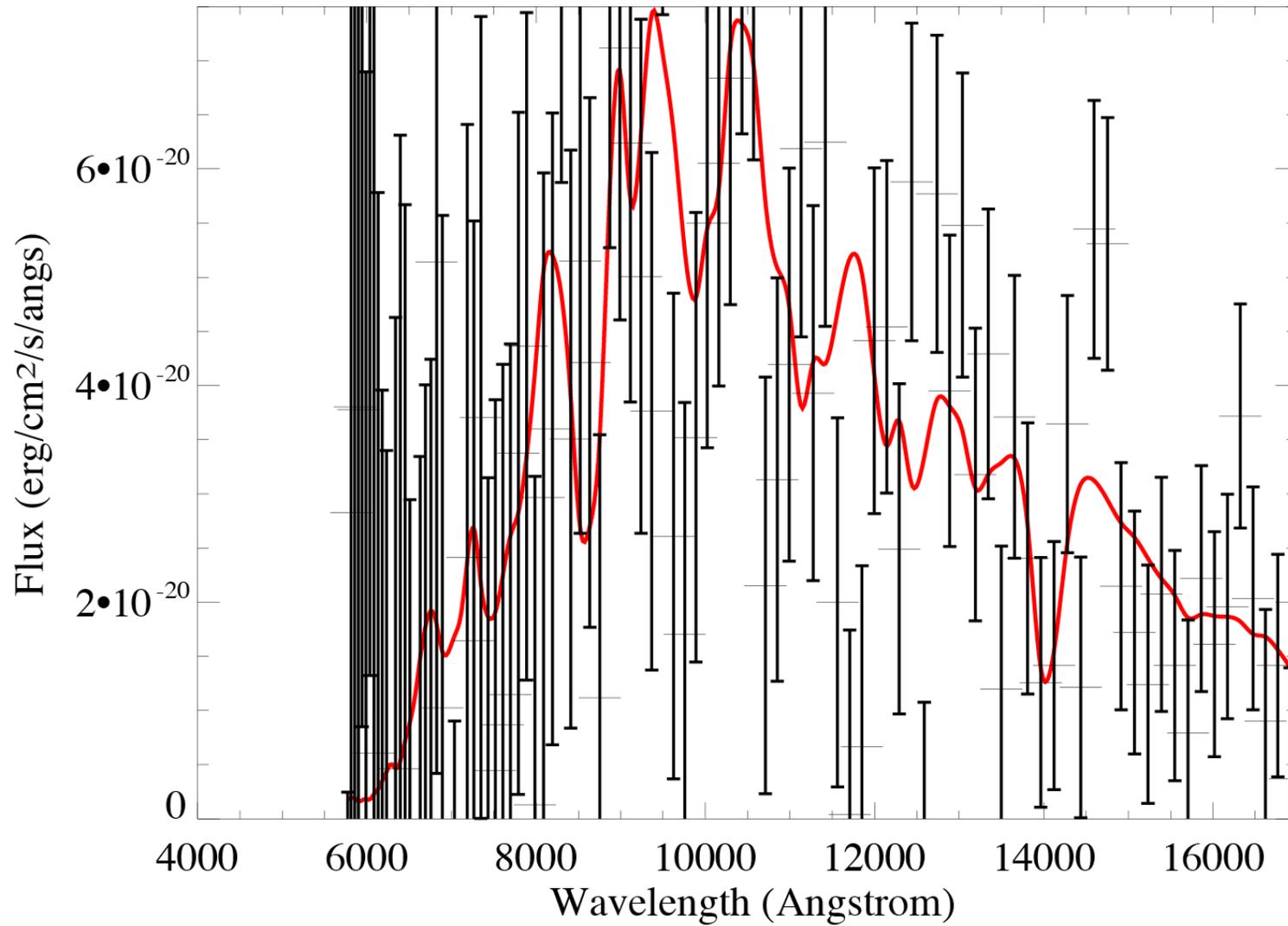
# IFU Spectrometer, Lightcurves from S[pectra

Use imaging to discover supernovae in two filters with  $S/N > 4$  in each

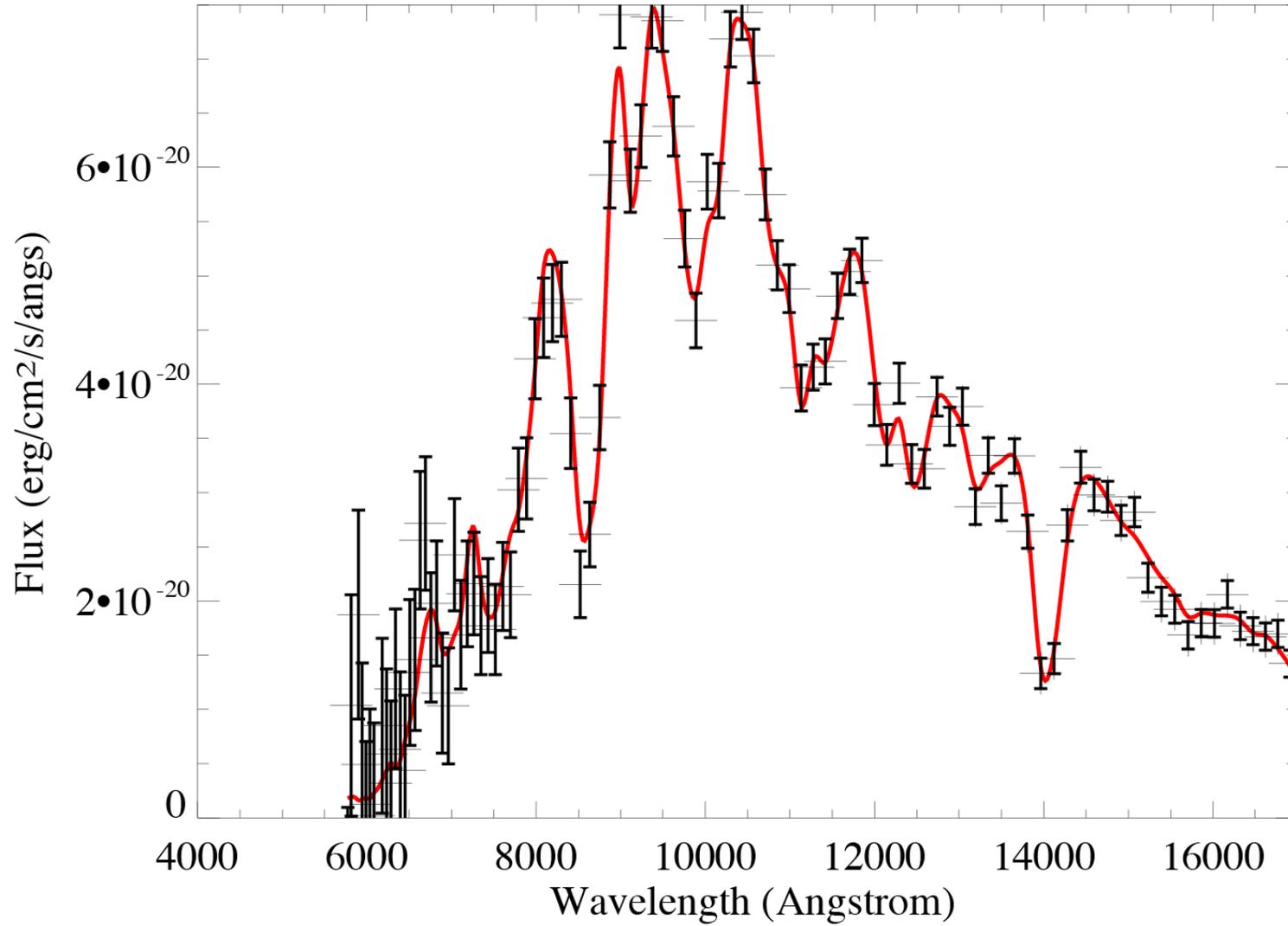
Use IFU spectrometer to get points on the lightcurve with  $S/N = 15$  per synthetic band ( $S/N = 3$  per pixel). Get an additional deep spectrum ( $S/N = 6$ ) near peak for subtyping and line ratios

Mode	Low z $z < 0.4$			Medium z $z < 0.8$			High z $z < 1.7$			Time per visit
	Area	Time	Hours	Area	Time	Hours	Area	Time	Hours	
Imaging Discovery	27.44	15	0.8	8.96	75	1.3	5.04	360	3.6	6
Spectra for lightcurves	27.44	varies		8.96	varies		5.04	varies		19
Deep Spectra	27.44	varies		8.96	varies		5.04	varies		8

# Signal-to-Noise of 1 SN Ia spectrum



# Signal-to-Noise of 7 SN Ia spectrum



## C. 2.4m IFU Deep Spectro Lightcurves, FoM=303

$\langle Z \rangle$	SNe Low z	SNe Mid z	SNe Hi z	SNe Total	$\sigma_{\text{stat}}$	$\sigma/\sqrt{N}$	$\sigma_{\text{sys}}$	$\sigma_{\text{tot}}$
• 0.15	41	13	7	61	0.150	0.019	0.006	0.020
• 0.25	123	39	21	184	0.150	0.011	0.007	0.013
• 0.35	239	76	41	356	0.150	0.008	0.008	0.011
• 0.45	0	127	69	196	0.150	0.011	0.008	0.013
• 0.55	0	186	101	287	0.150	0.009	0.009	0.012
• 0.65	0	247	133	235	0.150	0.010	0.009	0.013
• 0.75	0	307	166	235	0.150	0.010	0.010	0.014
• 0.85	0	0	205	235	0.150	0.010	0.010	0.014
• 0.95	0	0	237	235	0.150	0.010	0.011	0.015
• 1.05	0	0	261	235	0.150	0.010	0.011	0.015
• 1.15	0	0	273	235	0.150	0.010	0.012	0.015
• 1.25	0	0	274	235	0.150	0.010	0.012	0.016
• 1.35	0	0	267	235	0.150	0.010	0.013	0.016
• 1.45	0	0	247	235	0.150	0.010	0.014	0.017
• 1.55	0	0	222	235	0.150	0.010	0.014	0.017
• 1.65	0	0	195	235	0.150	0.010	0.015	0.018
•								
•								

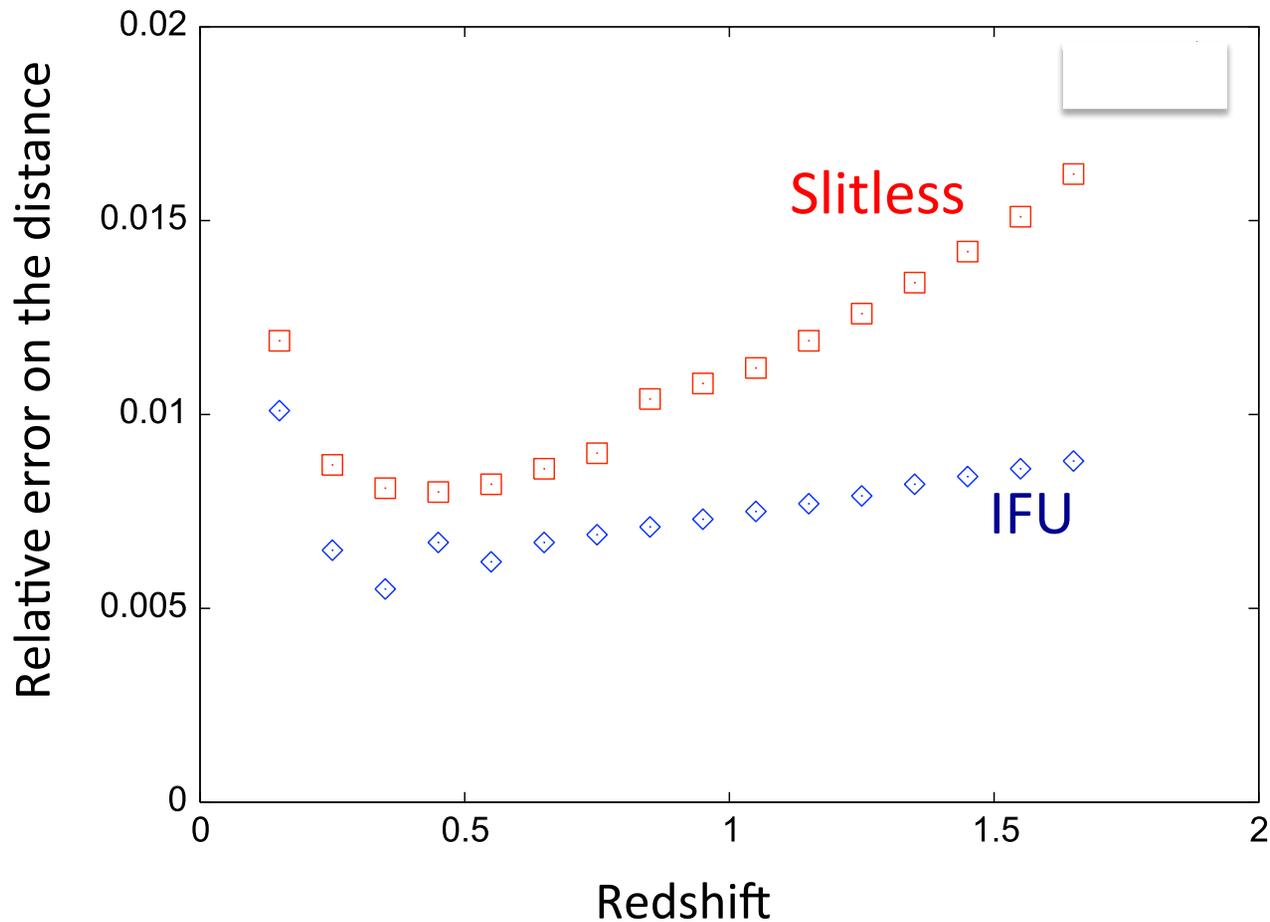
# Comparison of Performance

Survey Strategy	FoM
1.3 m DRM1 slitless, imaging lightcurves	153
1.1 m DRM2 slitless, imaging lightcurves	141
2.4 m DRM A slitless, imaging lightcurves	180
2.4 m DRM A slitless, spectro lightcurves	197
2.4 m DRM A IFU Deep spectro lightcurves	303

Comment: with the lower systematic errors with the IFU we could approach a FoM of 400 with extended time for the supernova survey

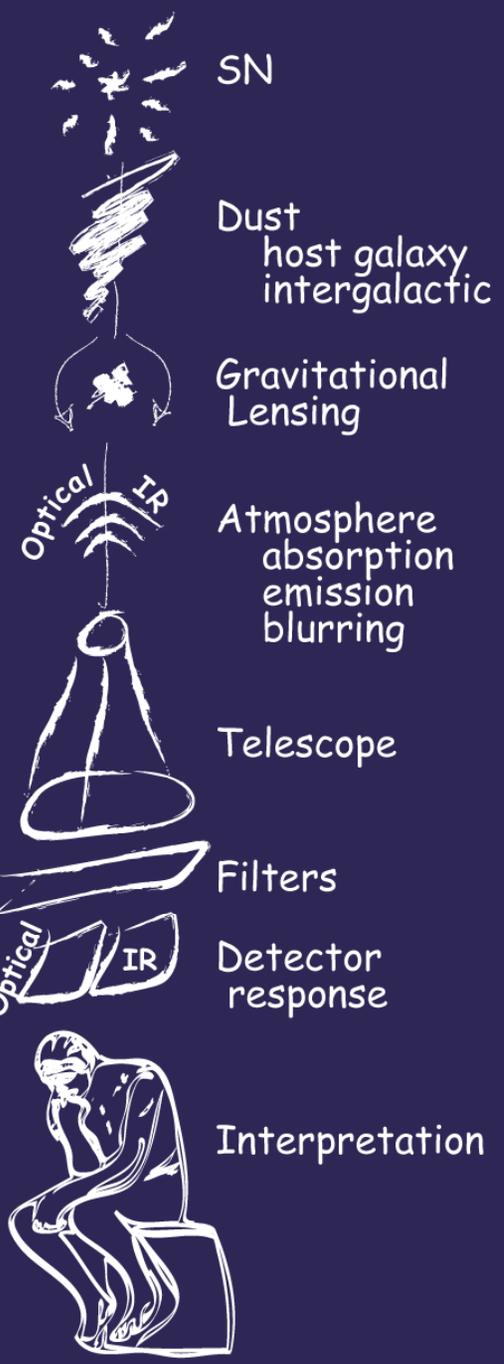
# Relative Error on the Distance

2.4 m mirror, 6 month supernova survey  
Lightcurves from spectroscopy



## Advantages of the 2.4 m Telescope

- With the 1.1 or 1.3 mirror, exposure times were long so supernova surveys planned to get lightcurves from imaging (requiring K corrections etc)
- With the 2.4 m mirror exposure times were short enough to get lightcurves from spectroscopy eliminating the need for K corrections.
- With the IFU spectrometer exposure times are even shorter and can get a deep spectrum to finally address the issue of evolution systematics by identifying subclasses using spectral features.



SN

Dust  
host galaxy  
intergalactic

Gravitational  
Lensing

Optical IR  
Atmosphere  
absorption  
emission  
blurring

Telescope

Filters

Optical IR  
Detector  
response

Interpretation

# Uncertainty & Bias - Both Natural and Man-Made

Type Ia ASTRO2010 *arXiv:0903.1086*

CURRENT ESTIMATES OF SYSTEMATIC ERRORS ON  $w$

Systematic	SNLS	ESSENCE	SDSS
Flux reference	0.053	0.02	0.037
Experiment zero points	0.01	0.04	0.014
Low-z photometry	0.02	0.005	...
Landolt bandpasses	0.01	...	0.019
Local flows	0.014	...	0.04
Experiment bandpasses	0.01	...	0.014
Malmquist bias model	0.01	0.02	0.017
Dust/Color-luminosity ( $\beta$ )	0.02	0.08	0.017
SN Ia Evolution	...	0.02	...
Restframe U band	...	...	0.08

NOTE. — Systematic error estimates on  $\langle w \rangle$  from Conley et al. (2009), Wood-Vasey et al. (2007), and Kessler et al. (2009).

Amanullah *et al.* 2010 (SCP)

Source	Error on $w$
Zero point	0.037
Vega	0.042
Galactic Extinction Normalization	0.012
Rest-Frame $U$ -Band	0.010
Contamination	0.021
Malmquist Bias	0.026
Intergalactic Extinction	0.012
Light curve Shape	0.009
Color Correction	0.026
<i>Quadrature Sum (not used)</i>	<i>0.073</i>
Summed in Covariance Matrix	0.063

Evolution

Low  $R_V$  &  
Intrinsic color

Landolt (!)  
Filters



SN



Dust  
host galaxy  
intergalactic



Gravitational  
Lensing



Atmosphere  
absorption  
emission  
blurring



Telescope



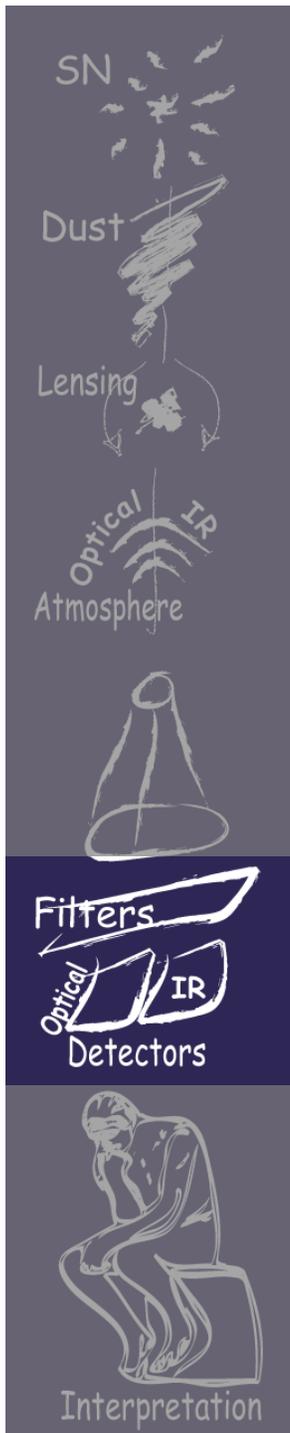
Filters



Detector  
response

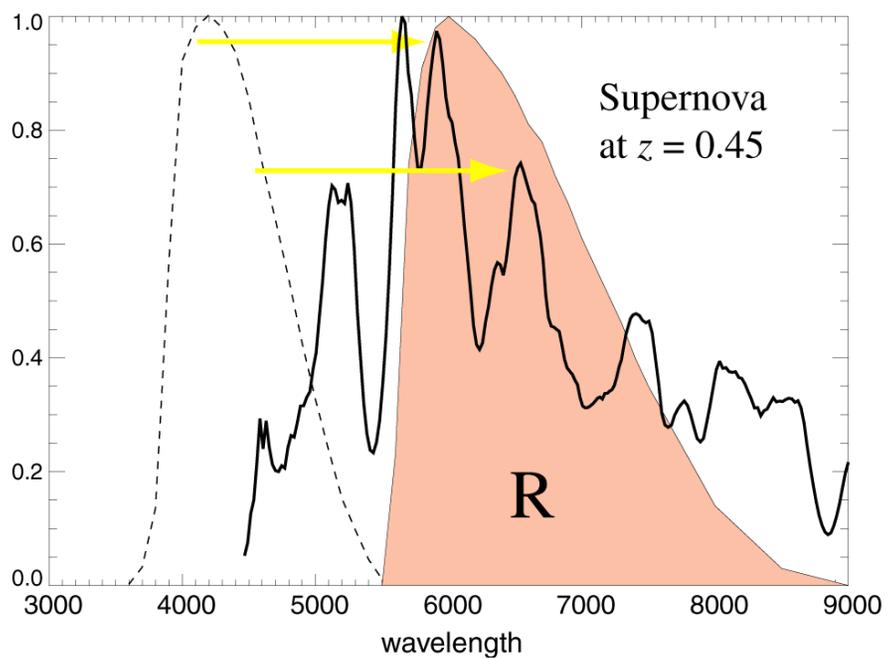
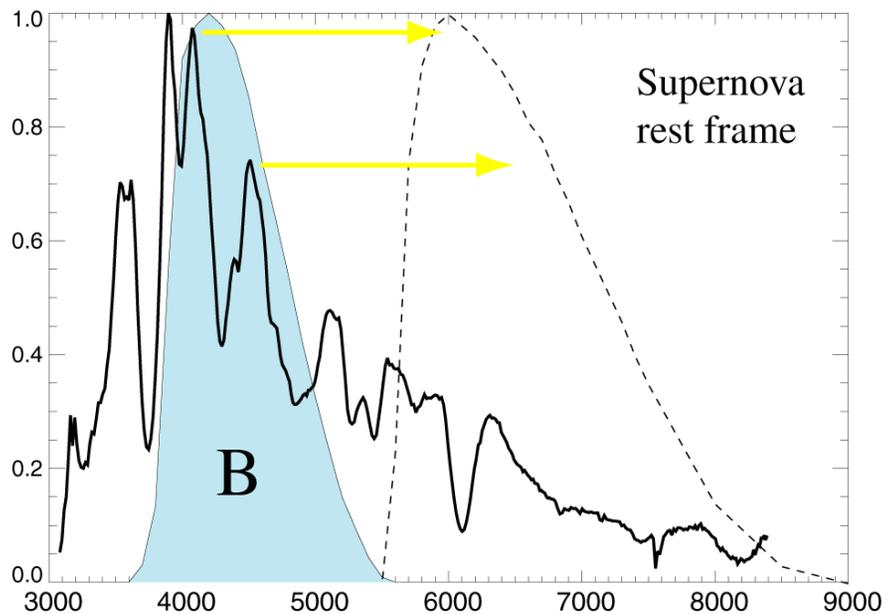


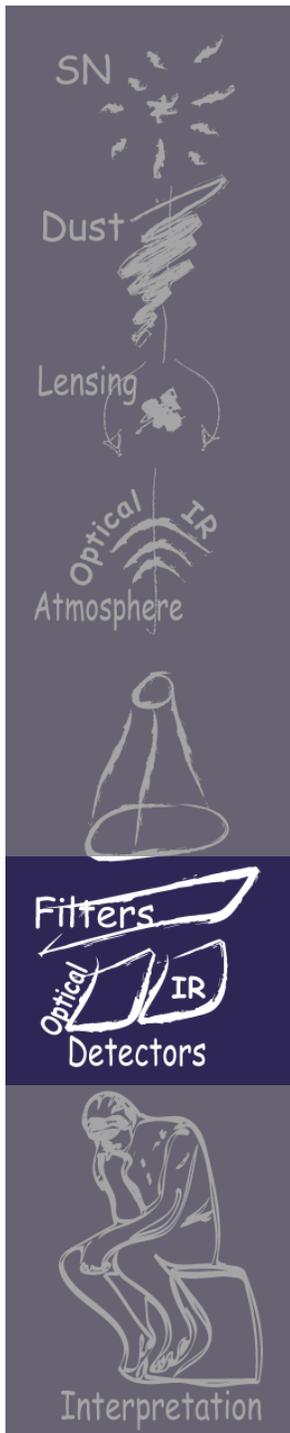
Interpretation



“Cross-Filter”  
K corrections

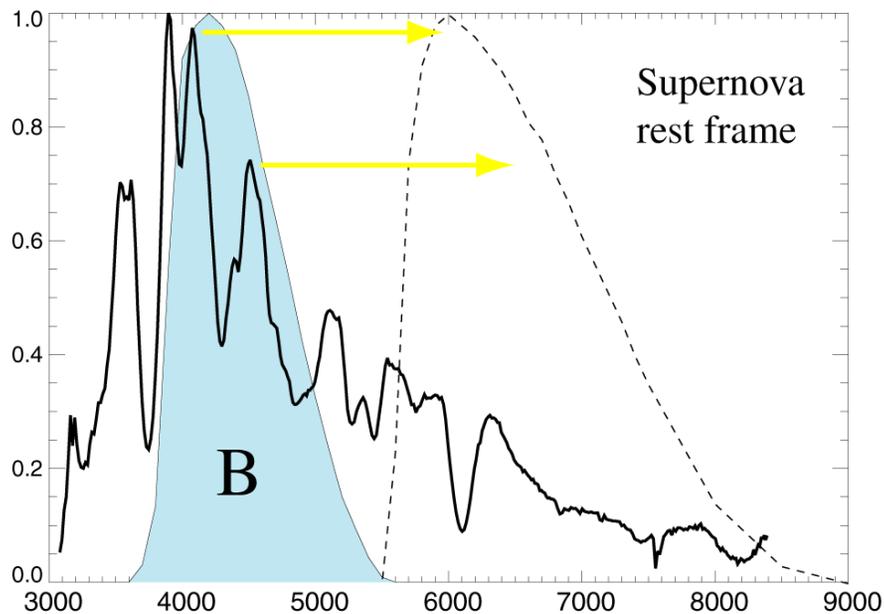
Kim, Goobar, & Perlmutter (1995)



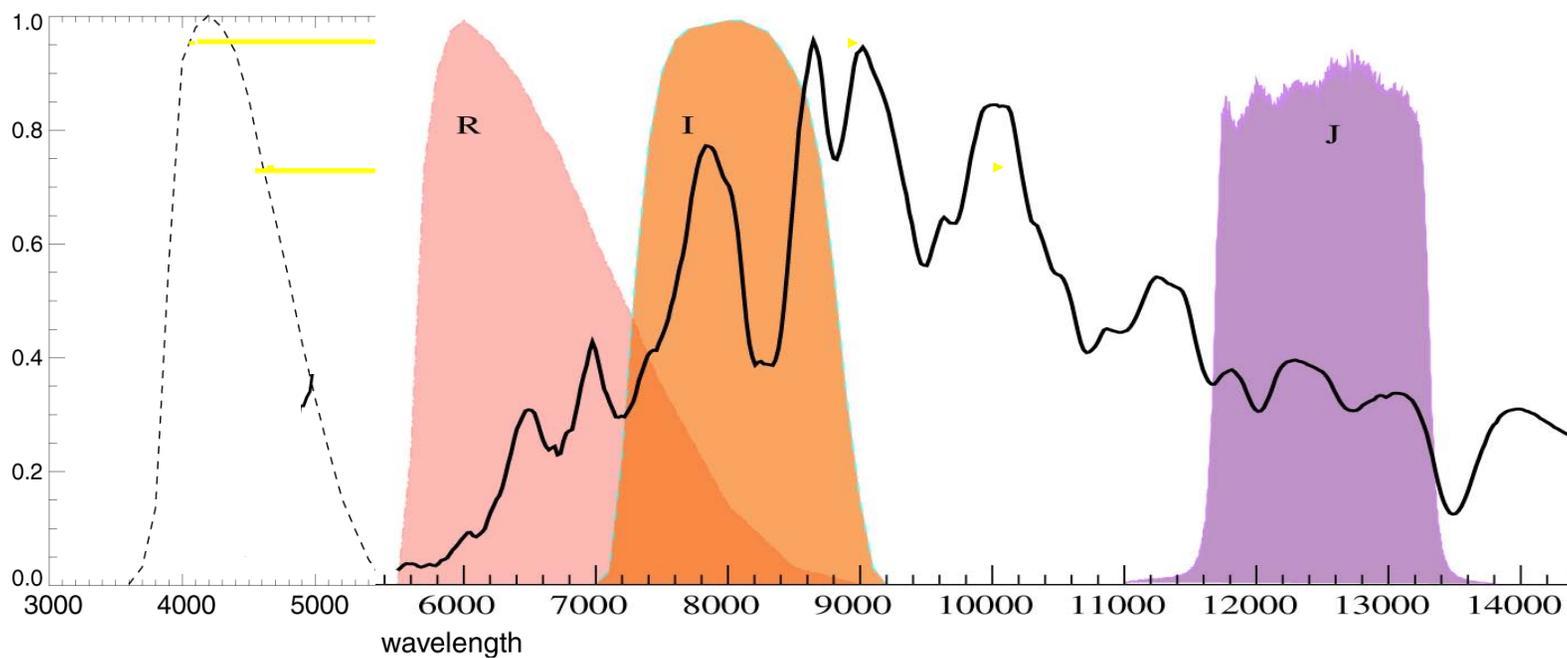


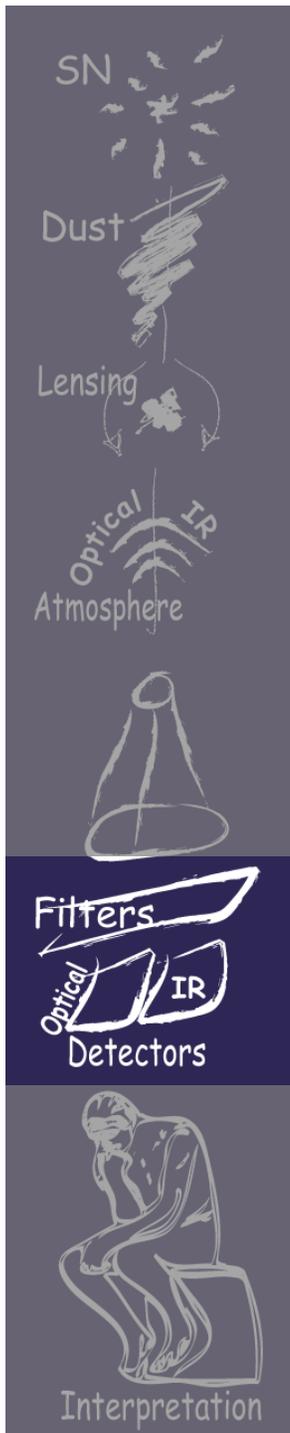
“Cross-Filter”  
K corrections

Kim, Goobar, & Perlmutter (1995)



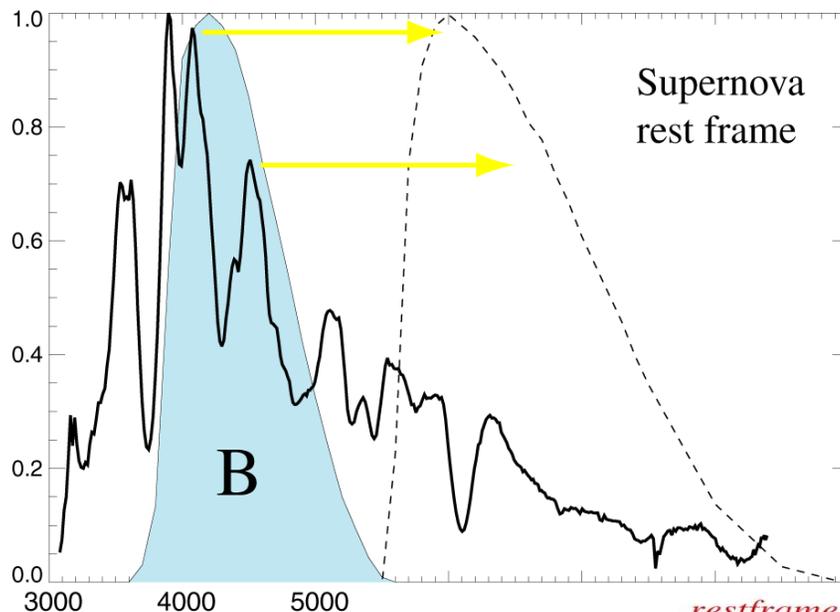
Supernova  
at  $z = 1.2$



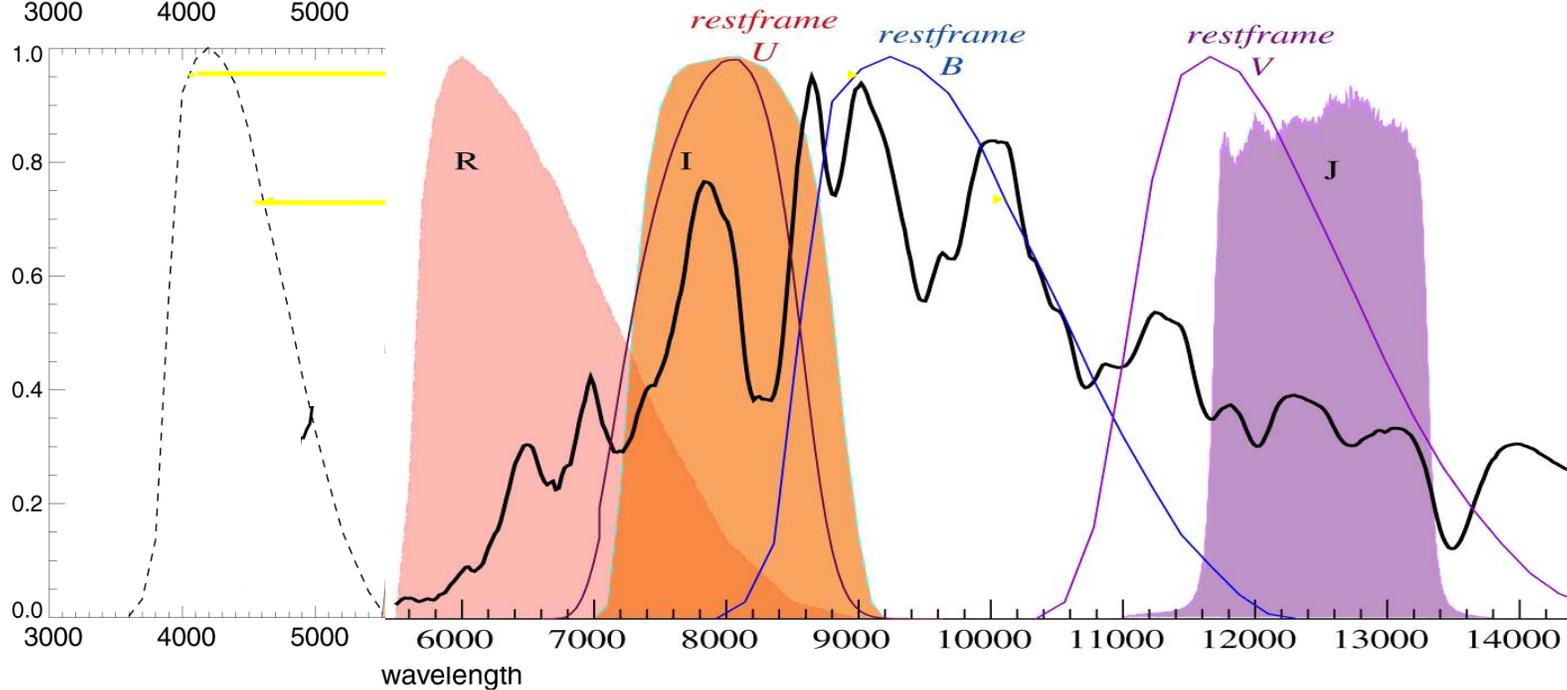


“Cross-Filter”  
K corrections

Kim, Goobar, & Perlmutter (1995)



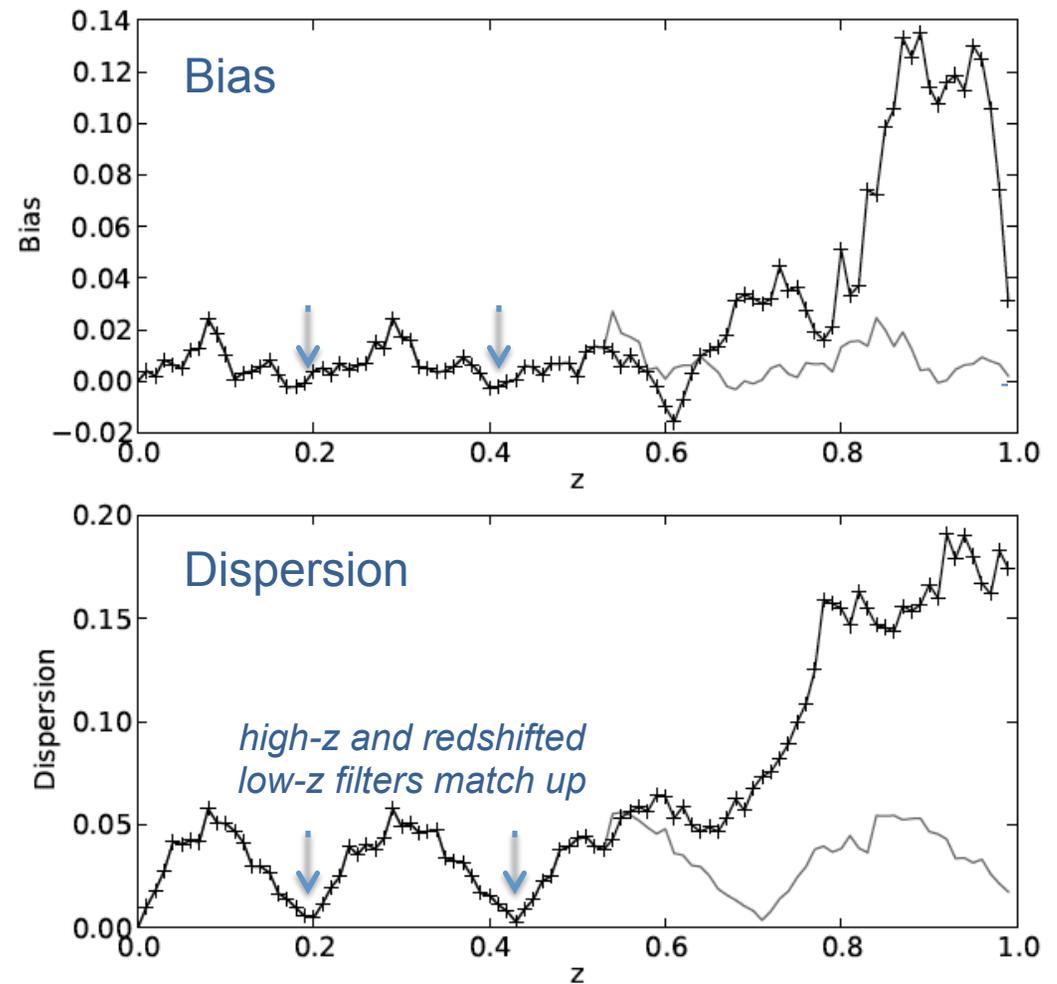
Supernova  
at  $z = 1.2$

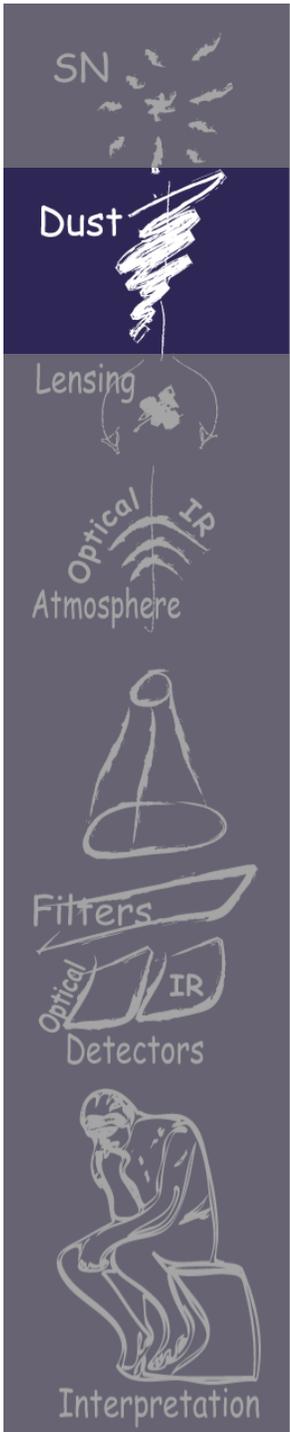


SNe Ia do not all show the exact same spectral time series, so the standard K corrections are not exact much of the time.

The distribution of K correction errors exhibits bias and dispersion whenever the high-redshift observations' filters don't exactly match the redshifted low-redshift observations' filters.

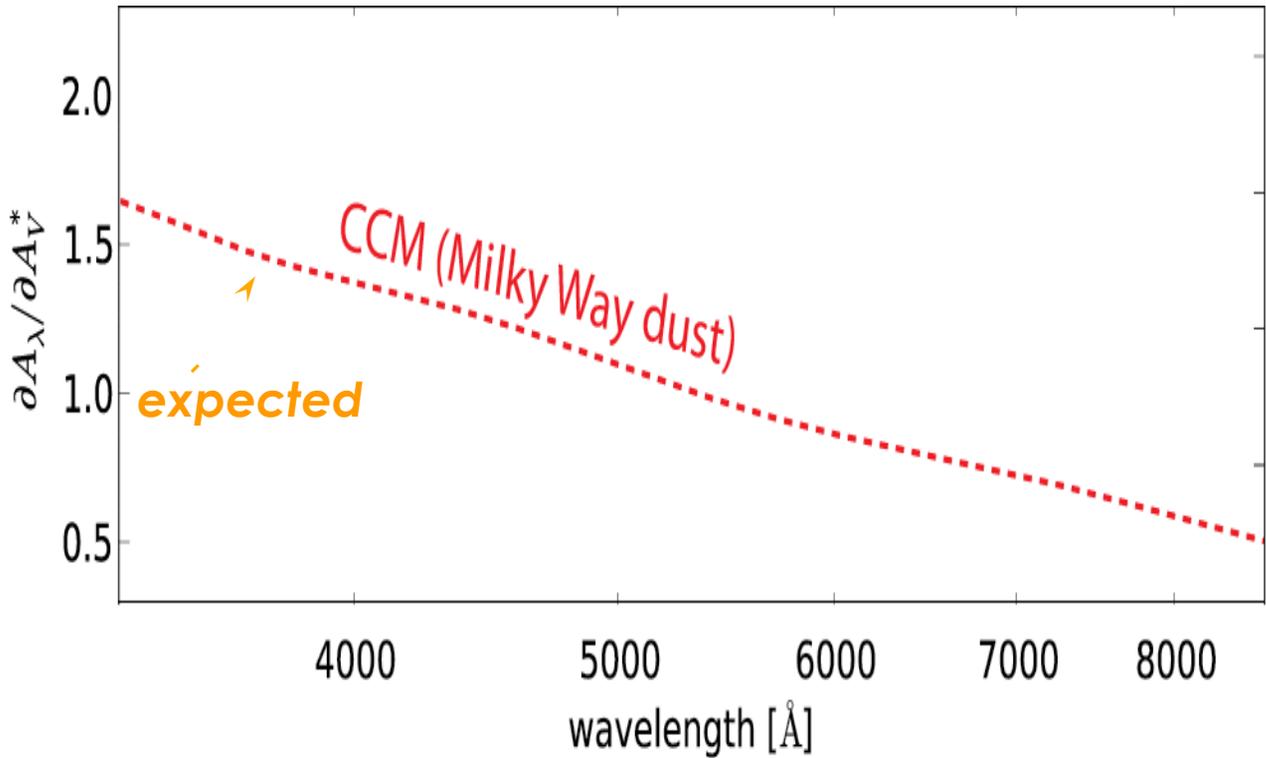
*Average error and dispersion on K-correction for a best-case logarithmically-spaced infinite filter set and for a finite number of logarithmically-spaced filters (SALT-2 fitter is used.)*





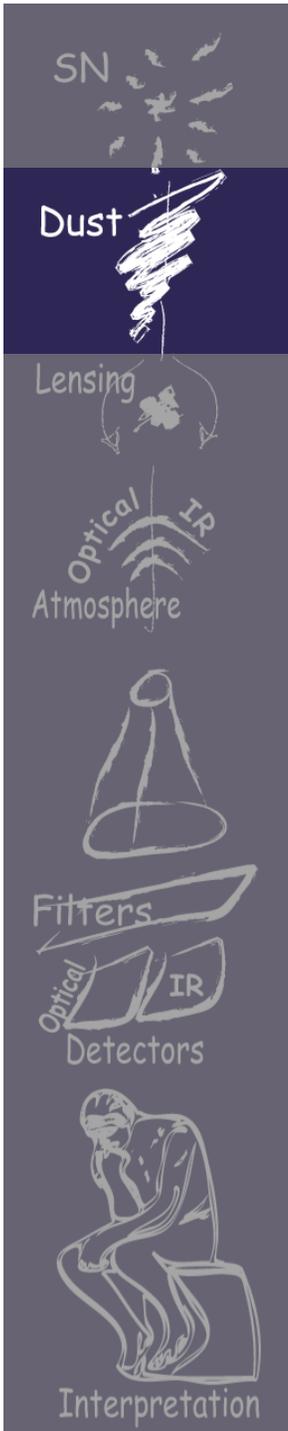
Dust absorbs/scatters the SN light more at blue wavelengths than at red wavelengths:

more dimming due to dust -



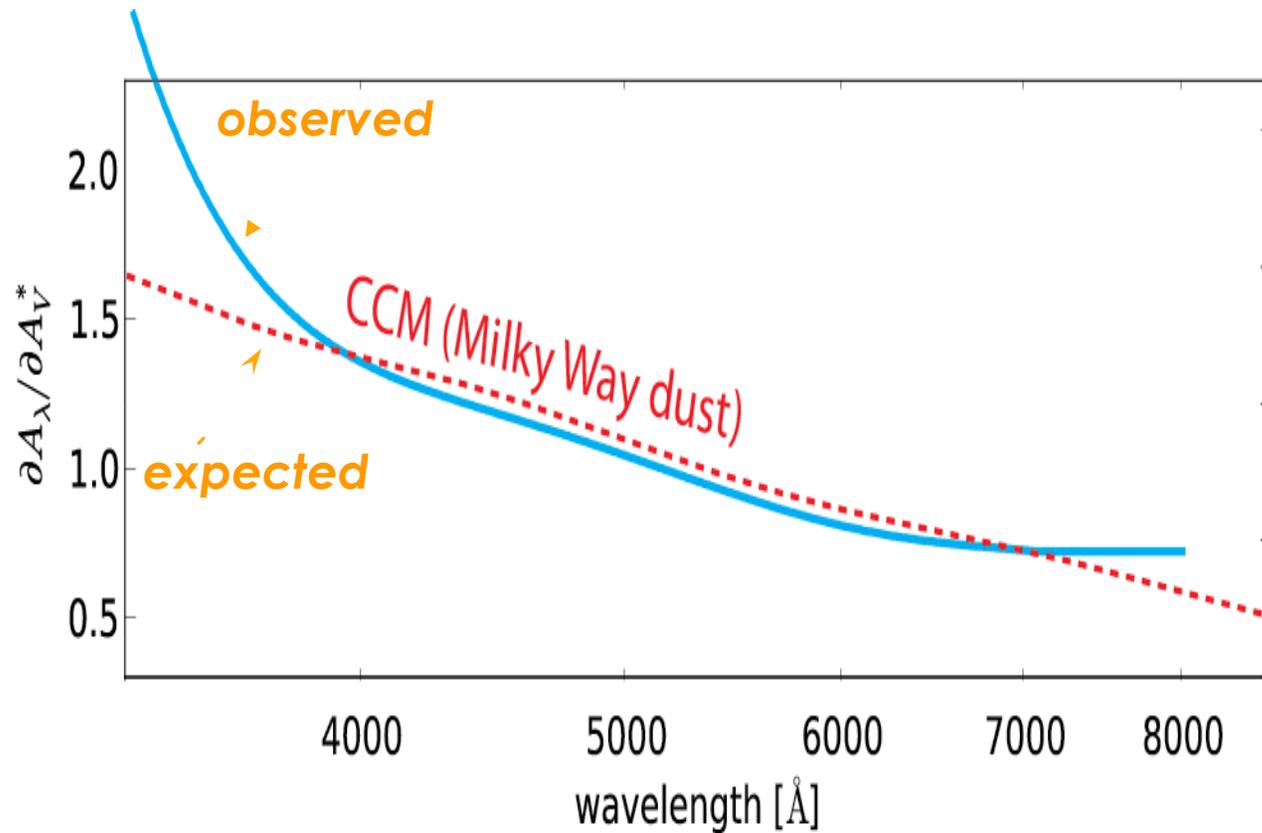
< - bluer

redder - >



Dust absorbs/scatters the SN light more at blue wavelengths than at red wavelengths:

more dimming due to dust -

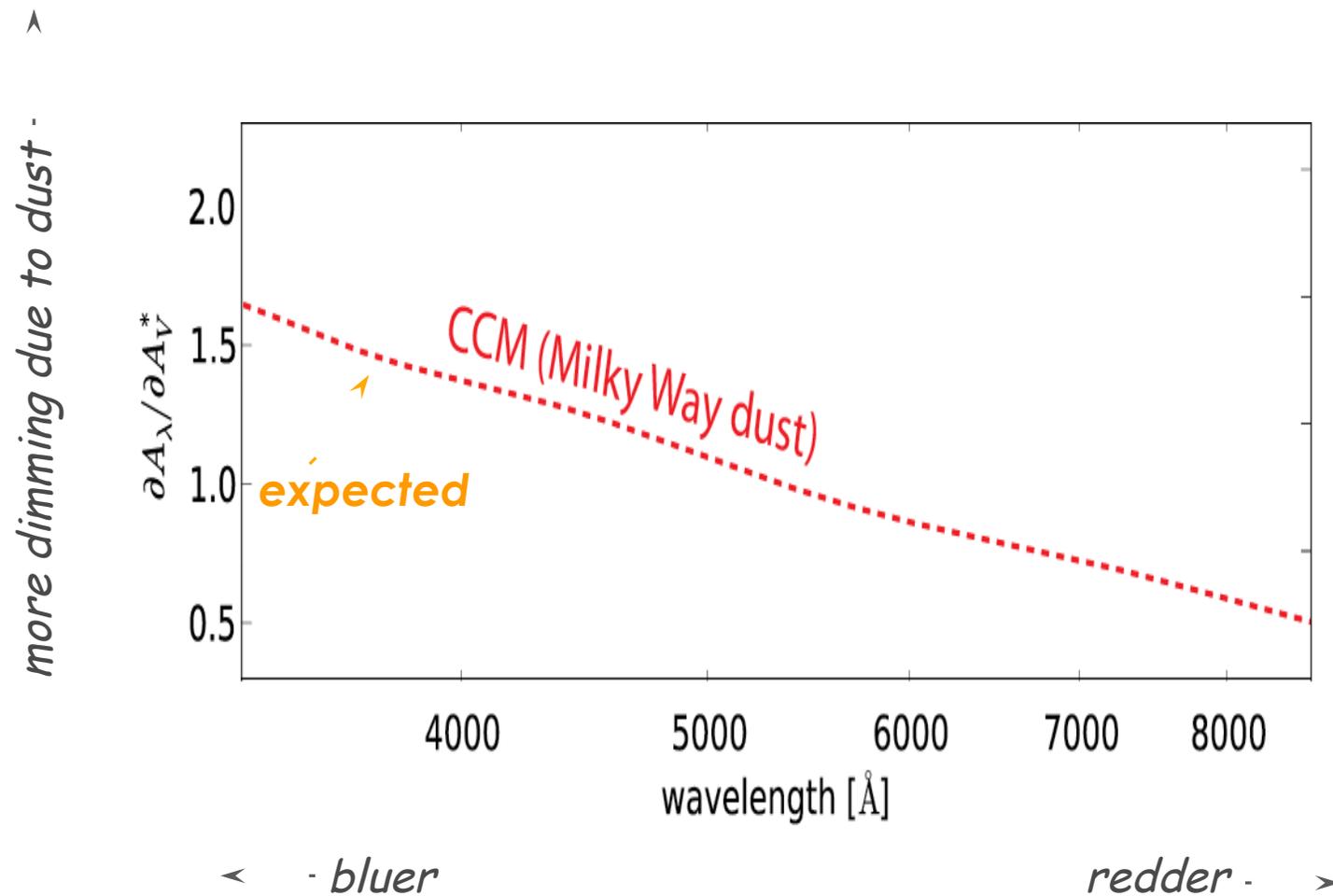


< - bluer

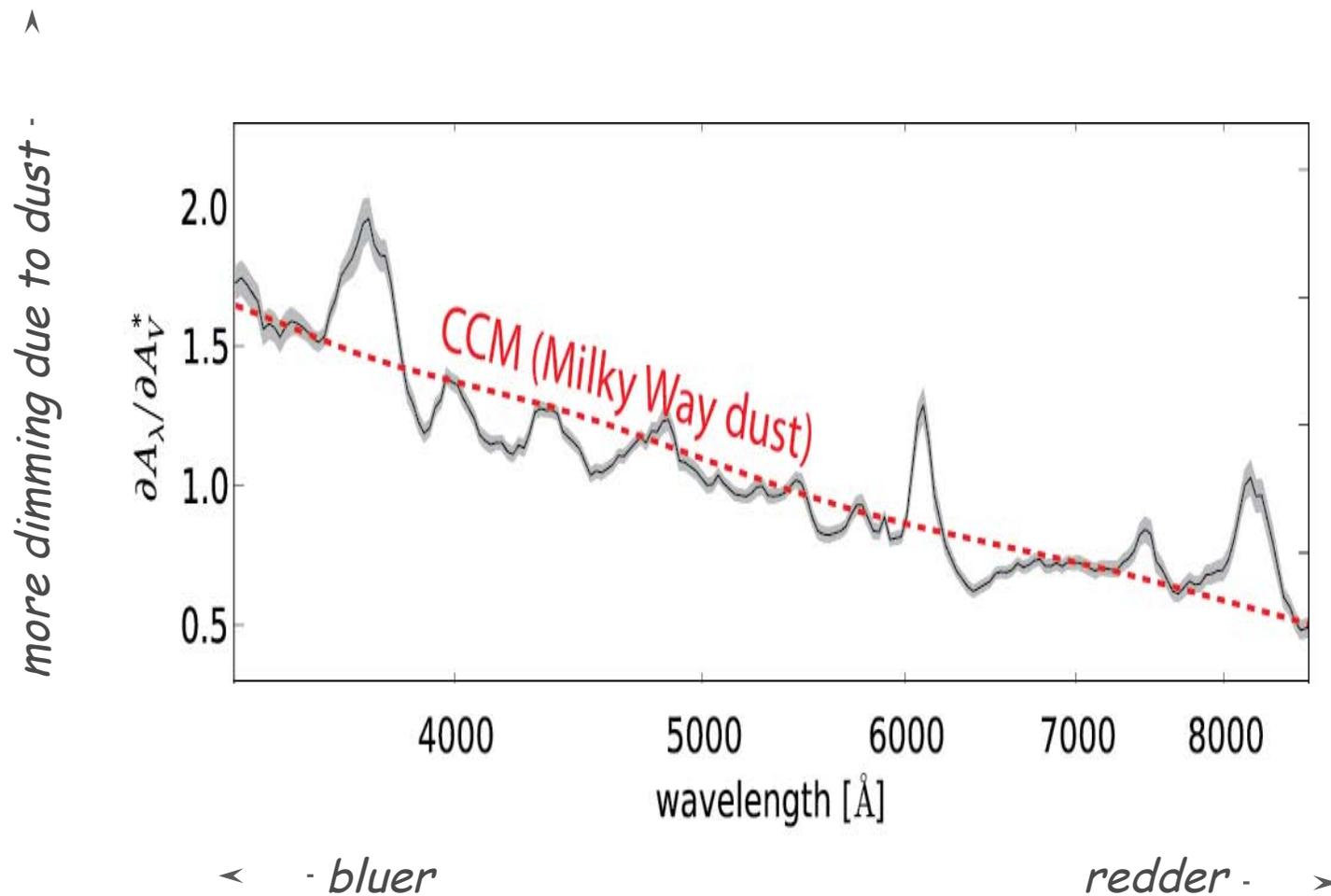
redder - >

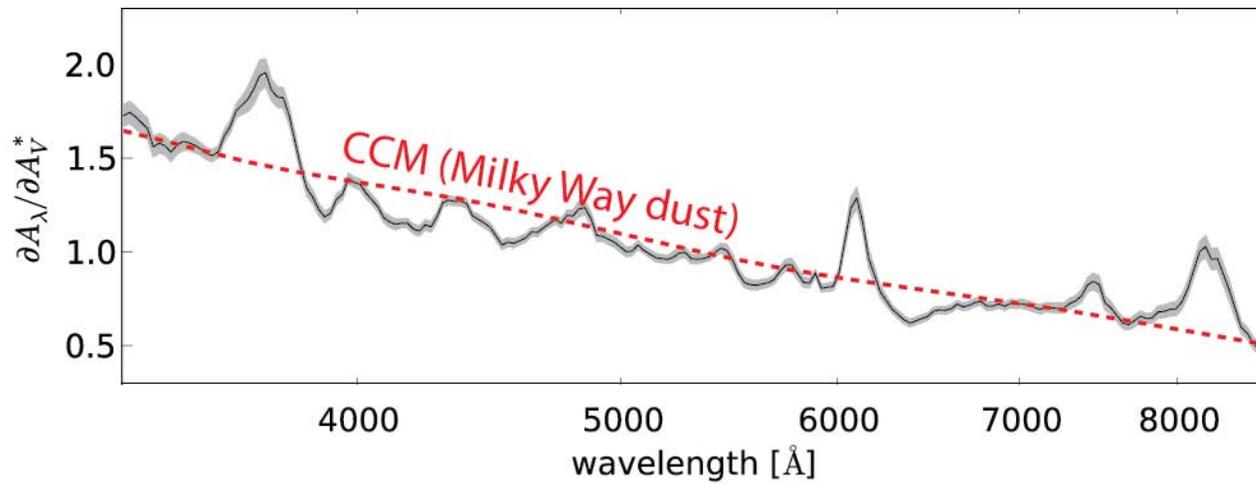
...but how do you tell this apart from differences in intrinsic SN color?

If we assume that all the color variation is due to dust ...

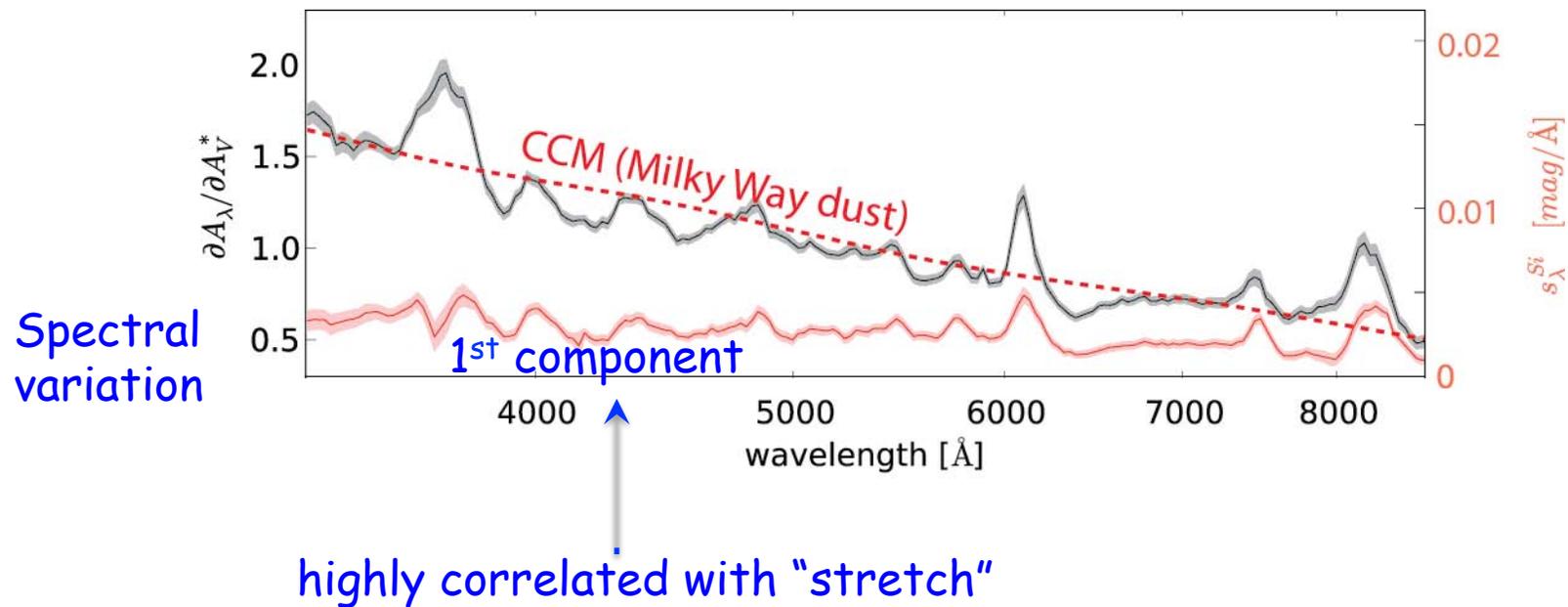


If we assume that all the color variation is due to dust we *don't* get CCM reddening law:

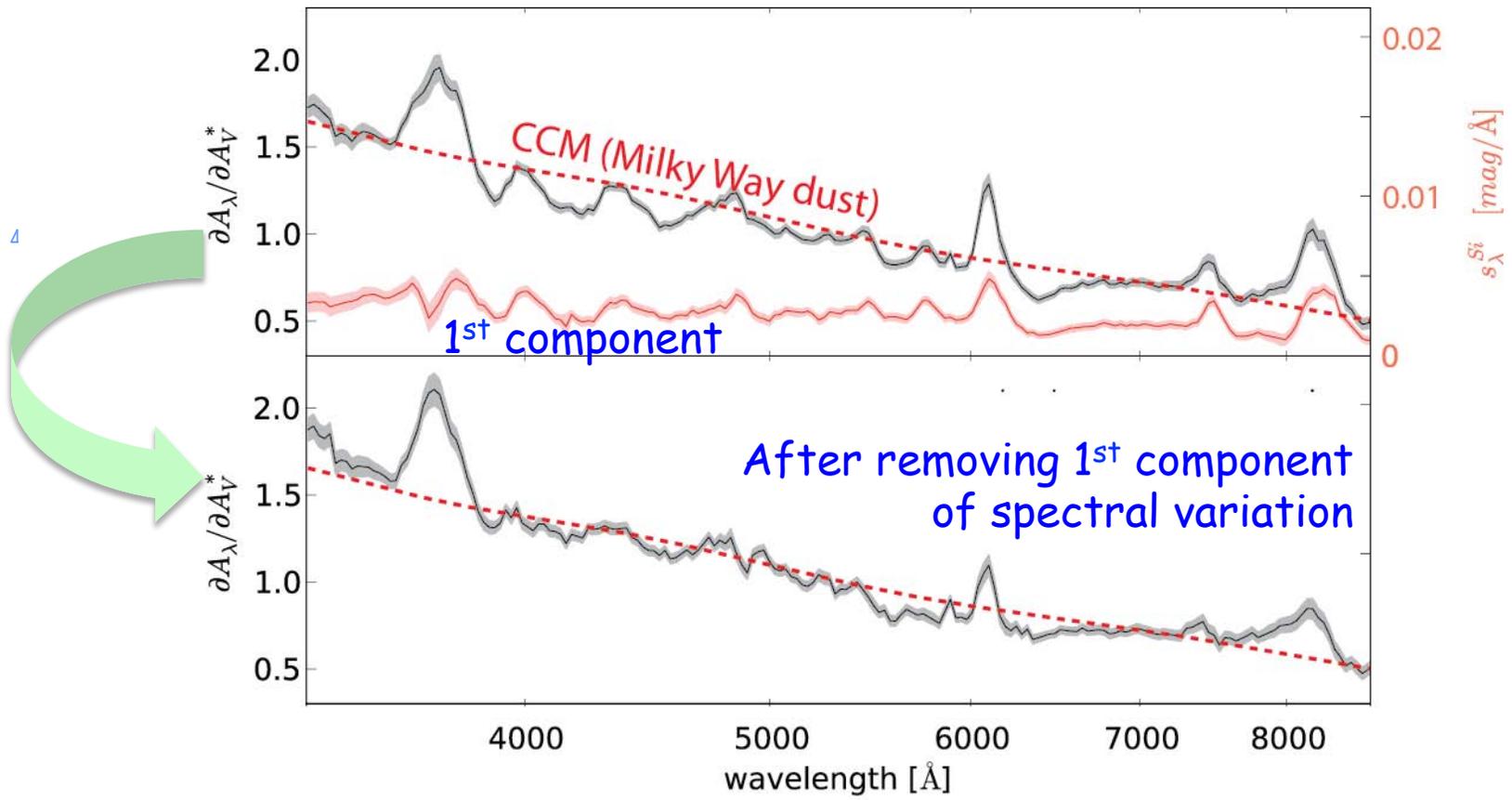




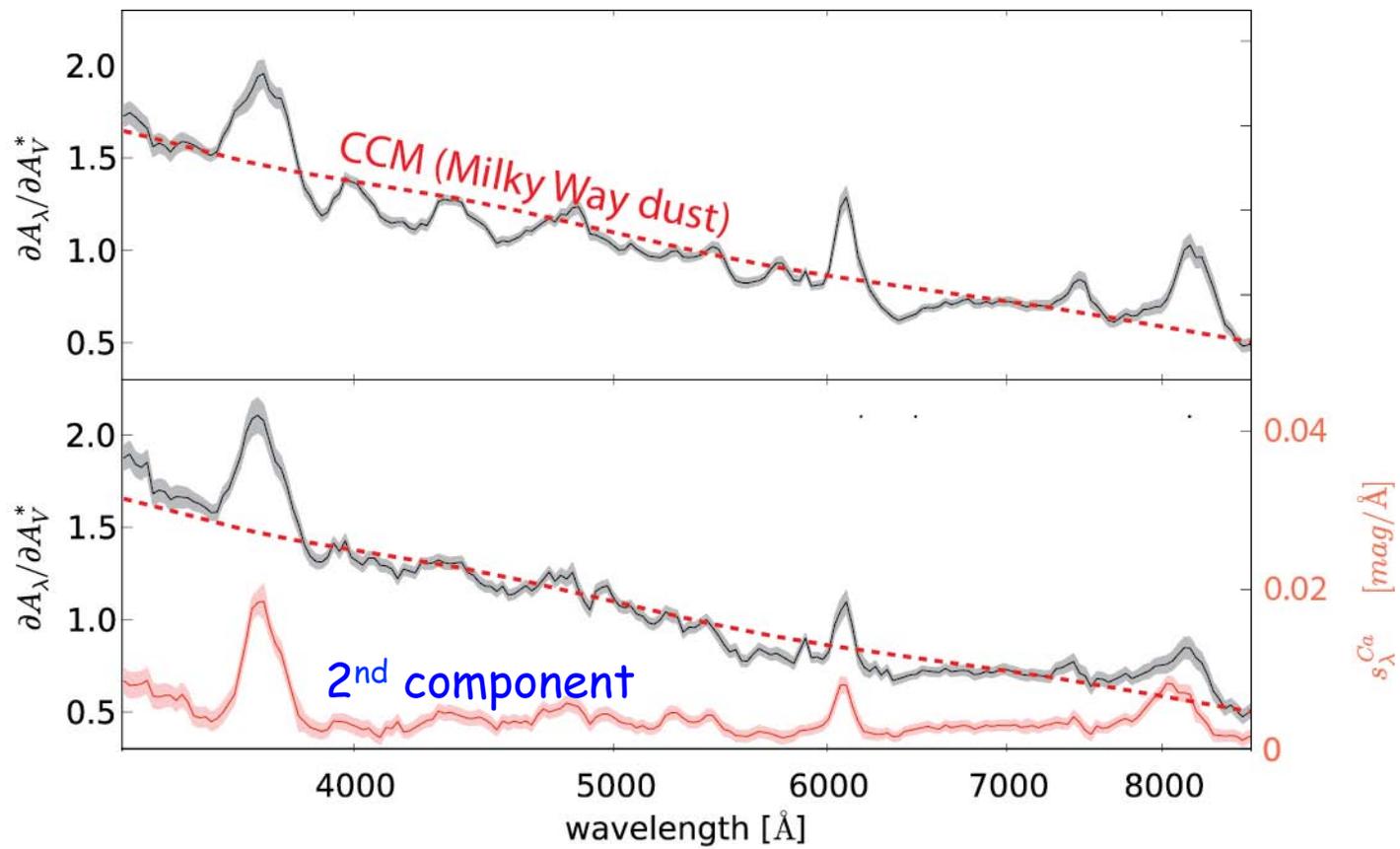
This is not surprising - we already know that there are spectral features associated with the "stretch" of the lightcurve timescale.



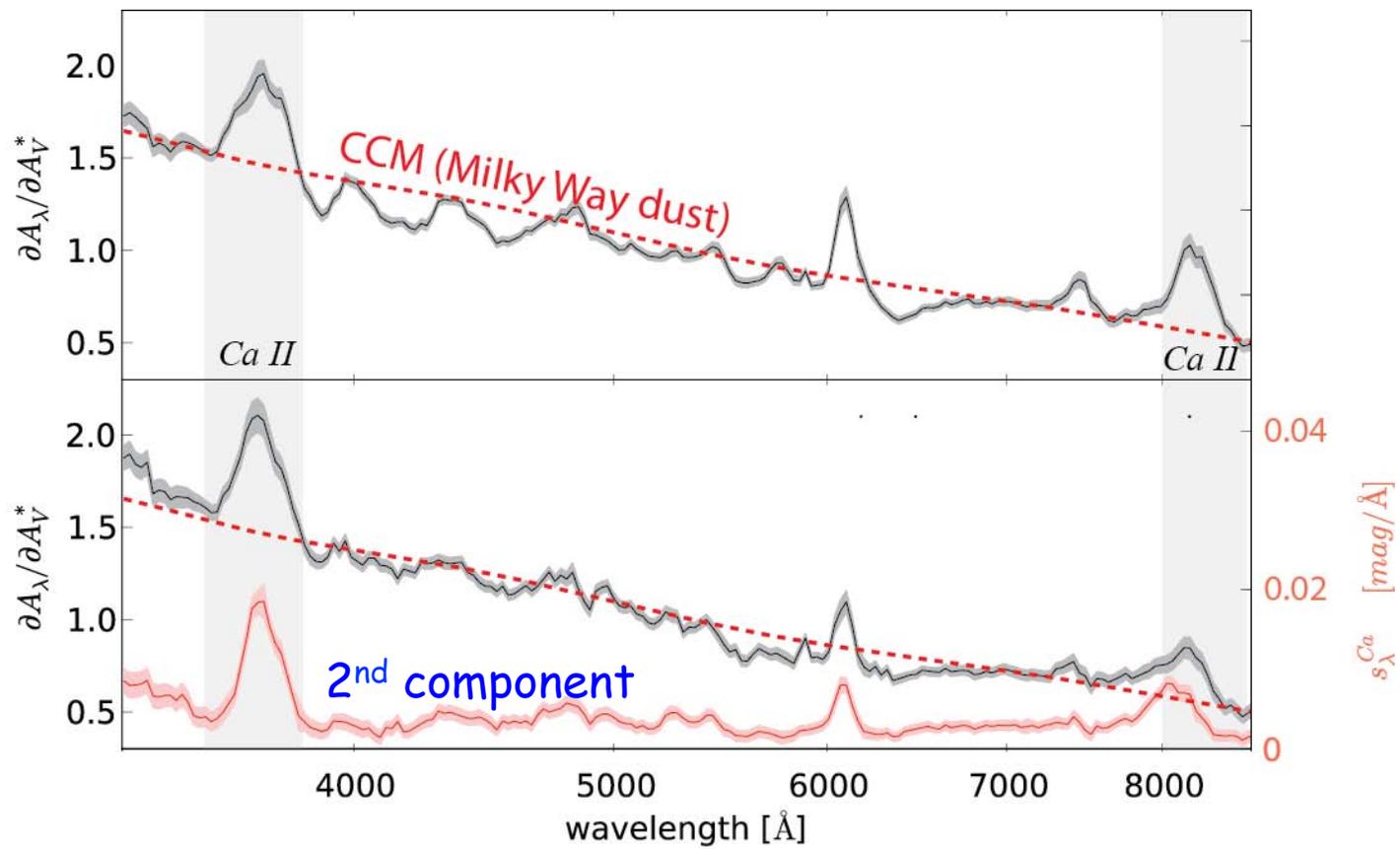
This is not surprising - we already know that there are spectral features associated with the "stretch" of the SN lightcurve timescale.

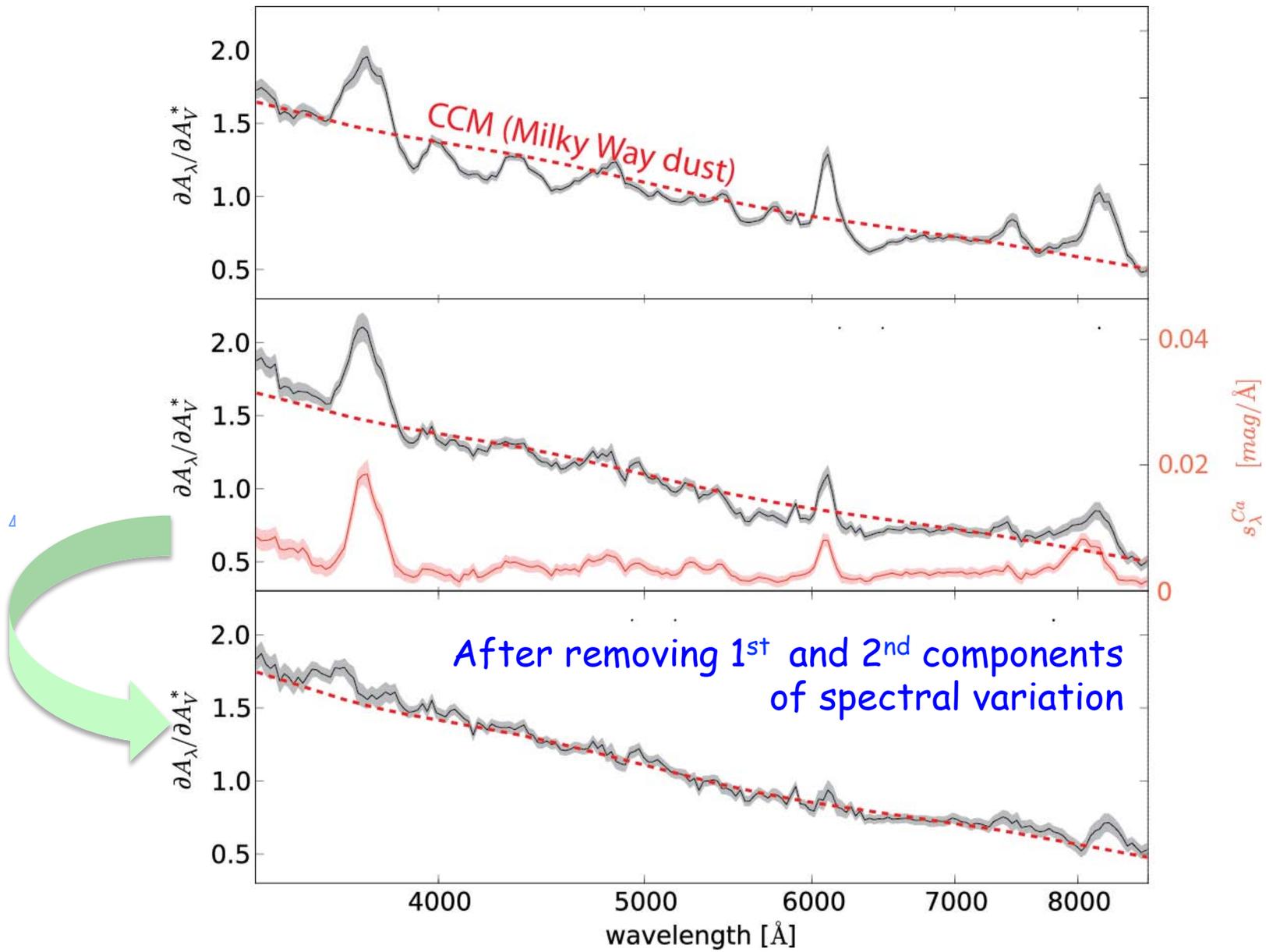


Spectral  
variation



Spectral  
variation

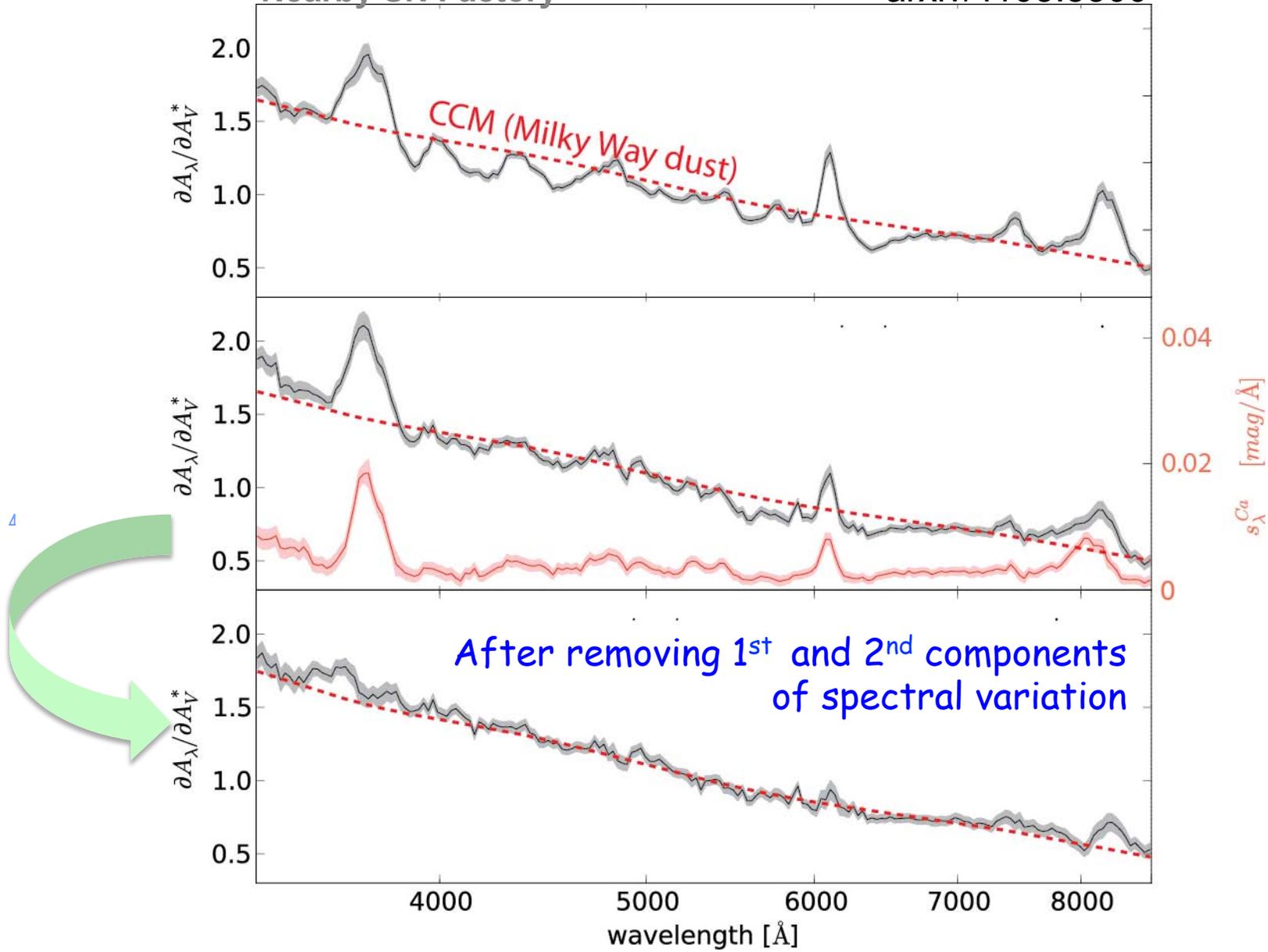


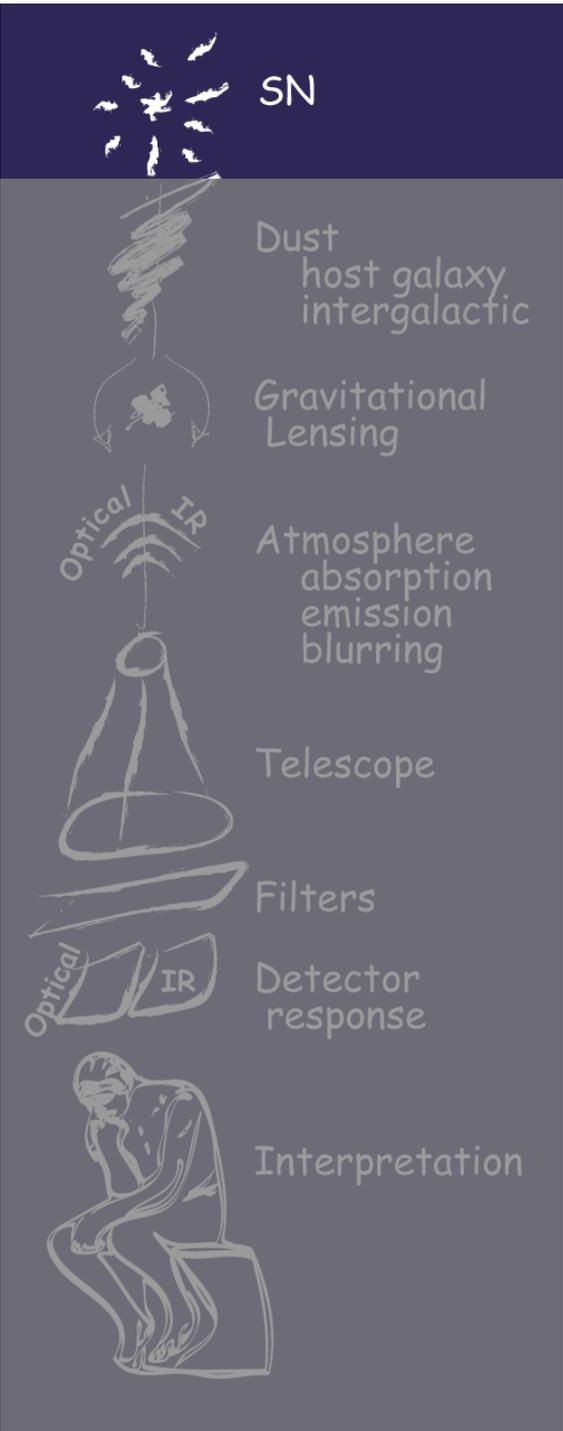


Chotard et al (A&A, 2011)

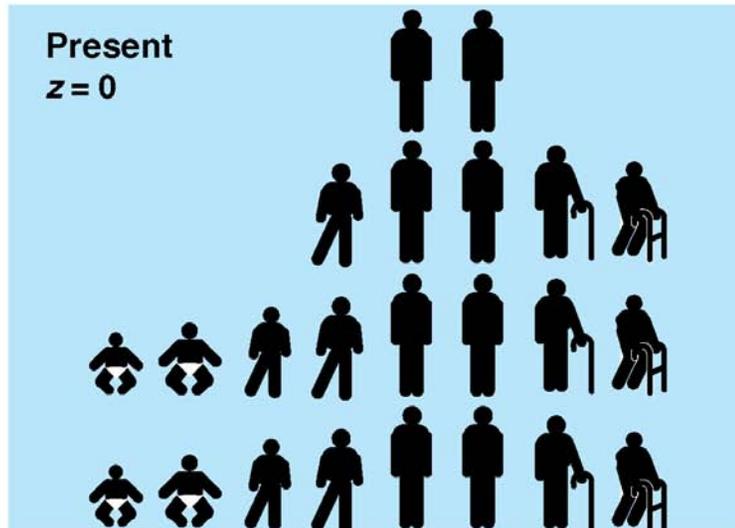
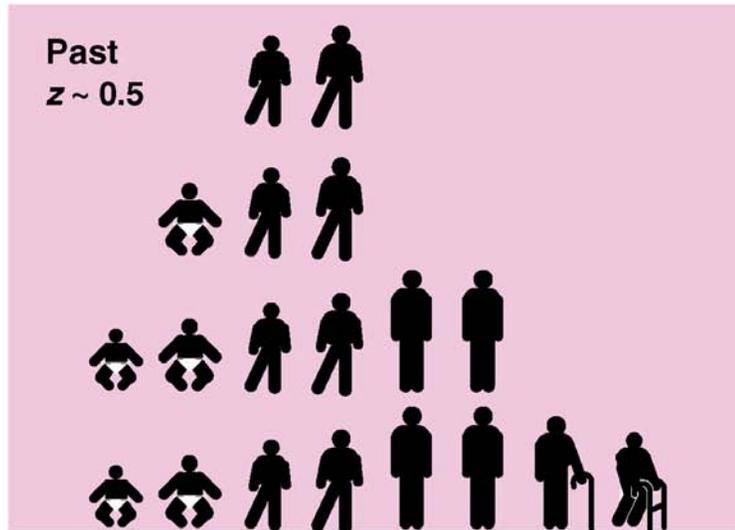
Nearby SN Factory

arxiv/1103.5300





## Supernova Demographics

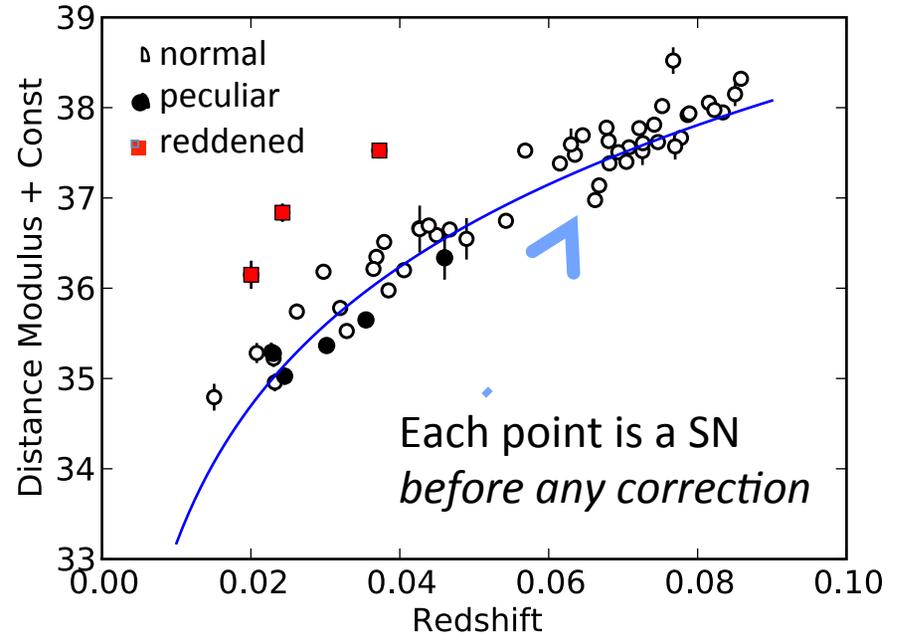
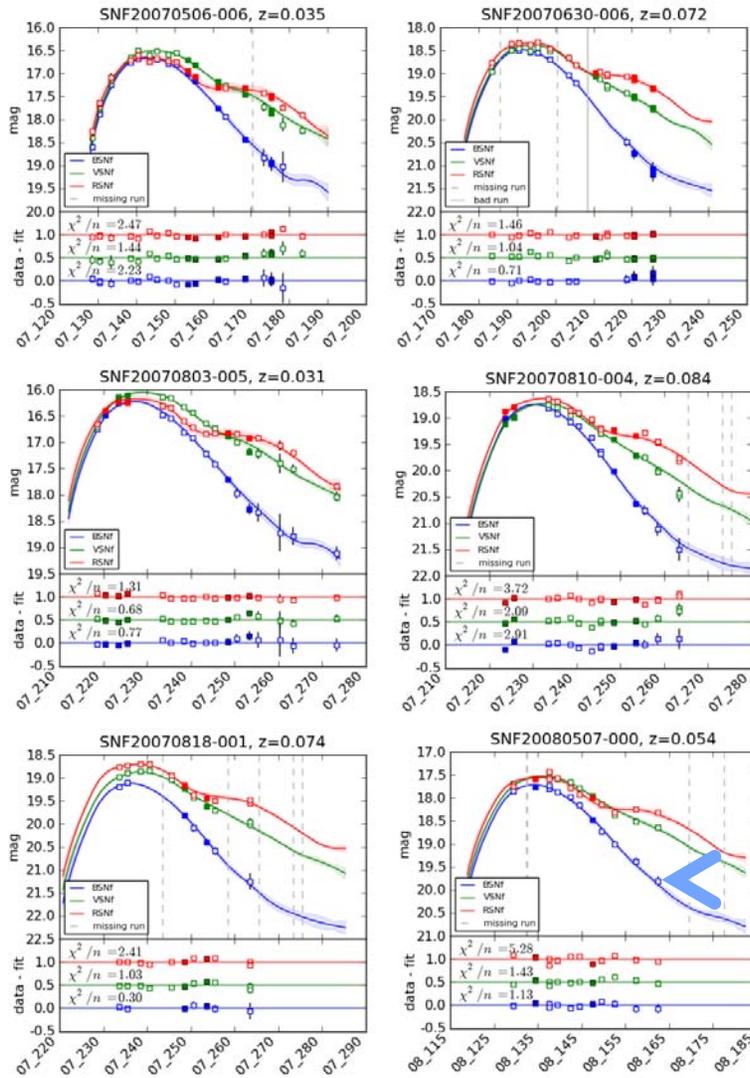


Galaxy Environment Age

← Younger

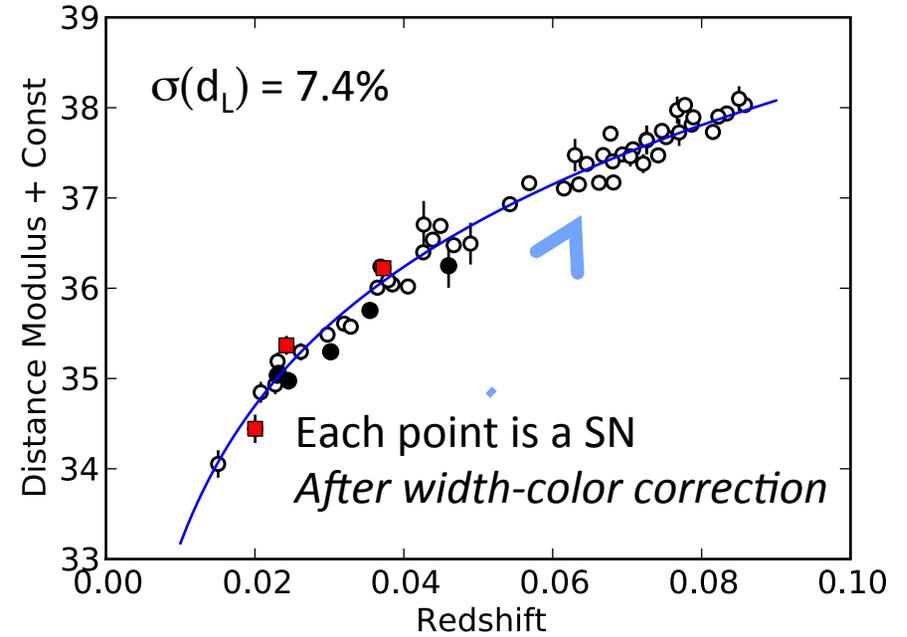
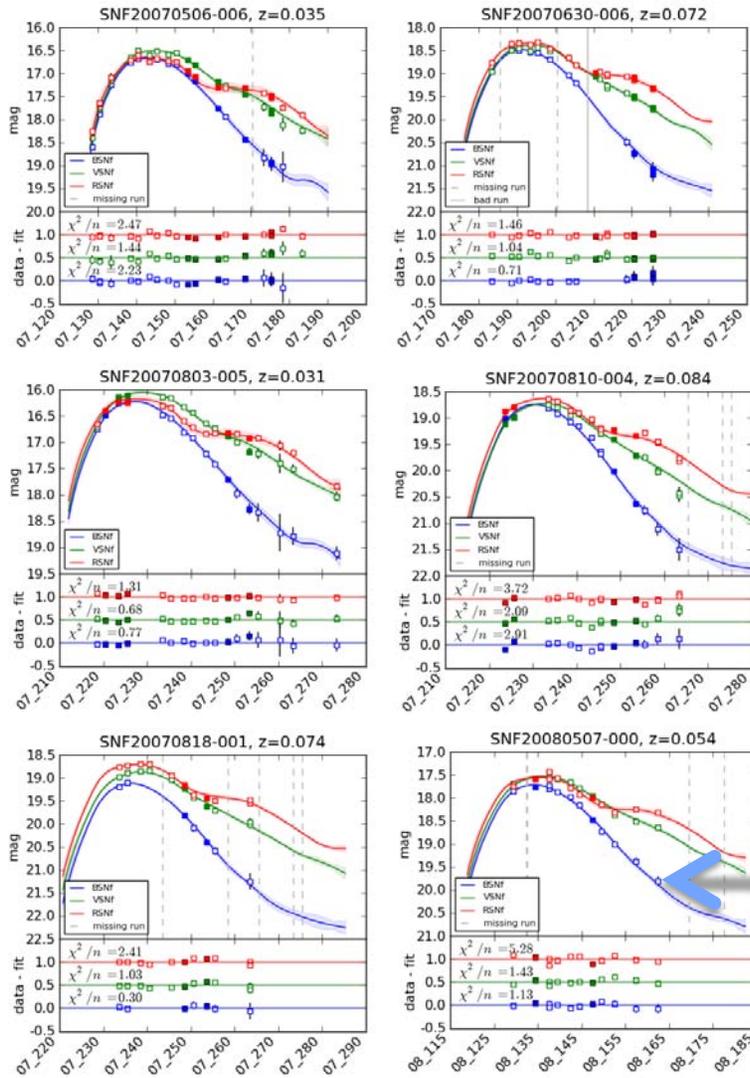
Older →

# Standardization



- Each point is synthesized photometry from a flux-calibrated spectrum

# Lightcurve Standardization



Each point is synthesized photometry from a flux-calibrated spectrum

# Lightcurve Standardization

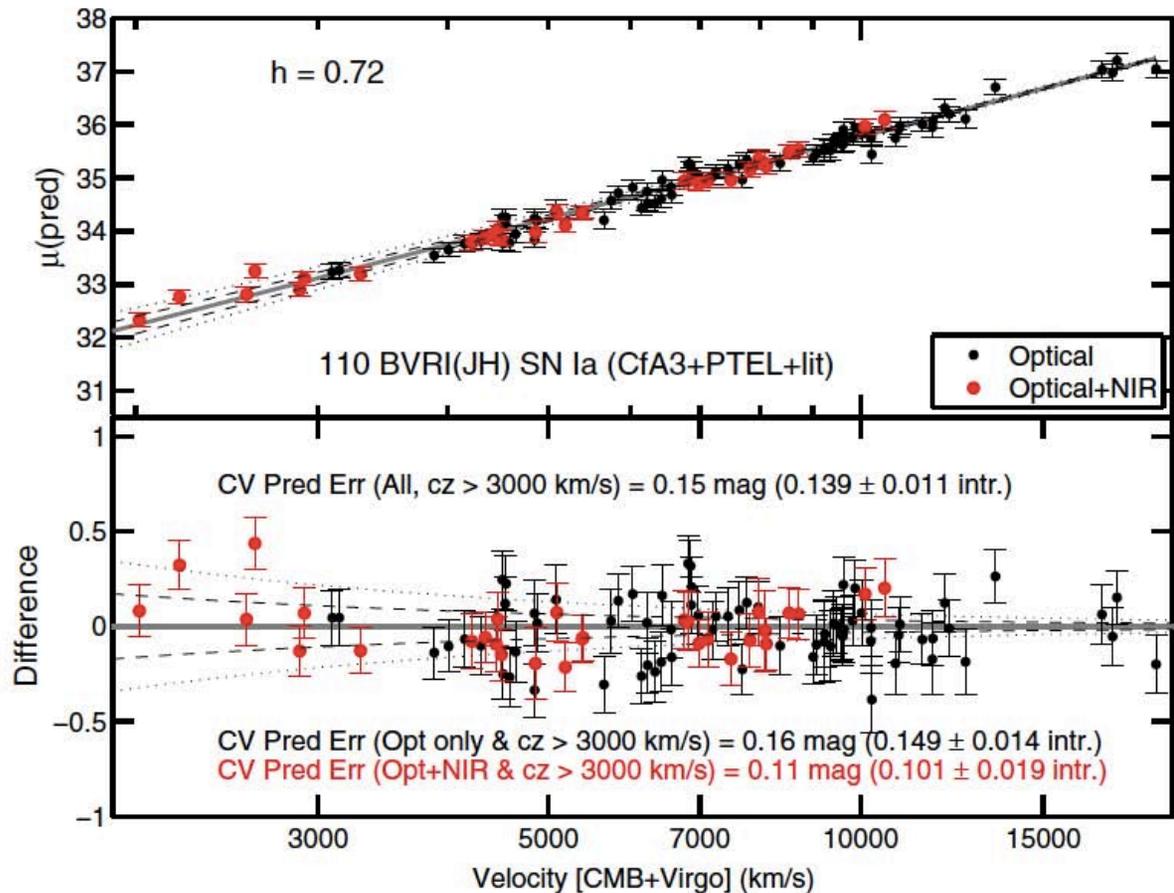
A route to better standardization:  
Add J and H band.

## Problems:

J band is not as big an improvement as H band.

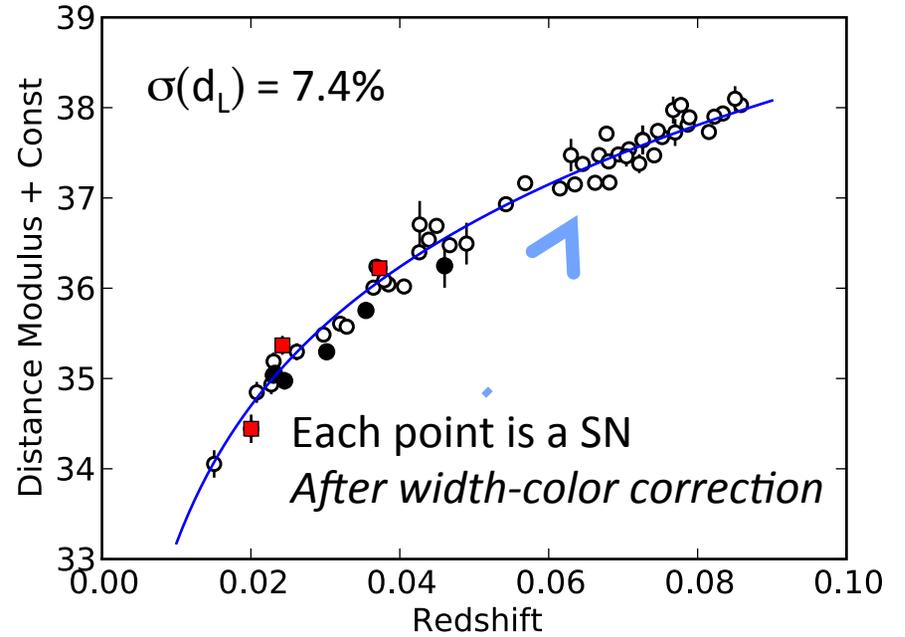
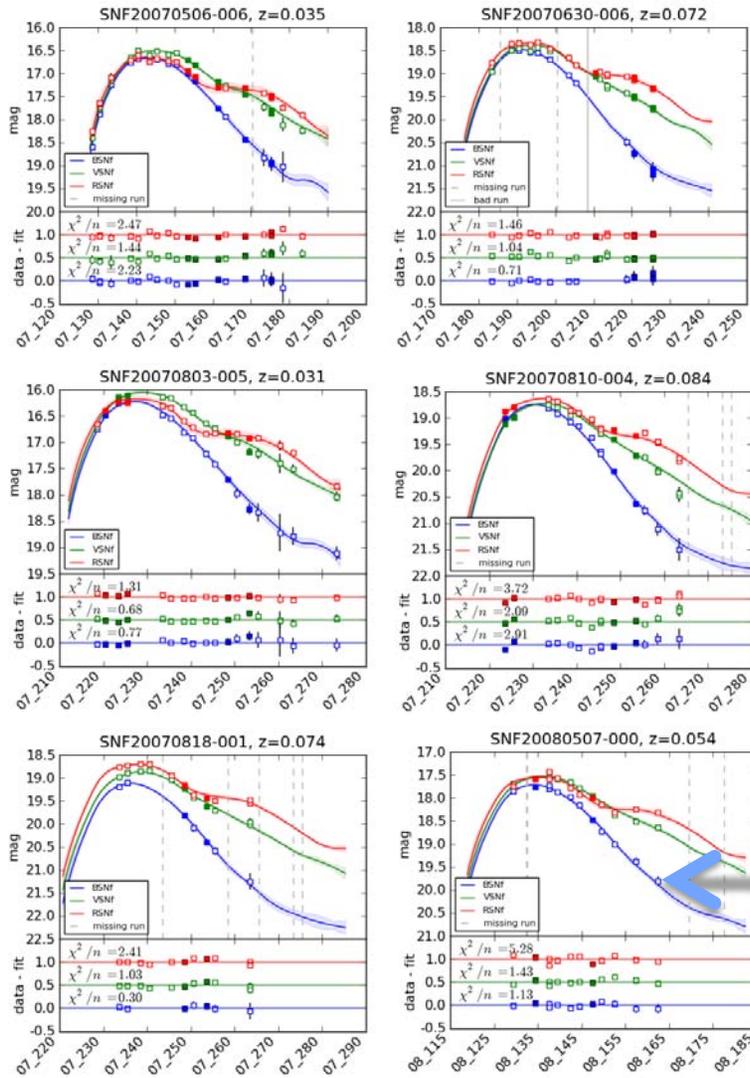
H band not available with HST WFC3.

With WFIRST can only obtain H band out to  $z = 0.12$  (with 2 micron cutoff) or  $z = 0.35$  with (2.5 micron cutoff).



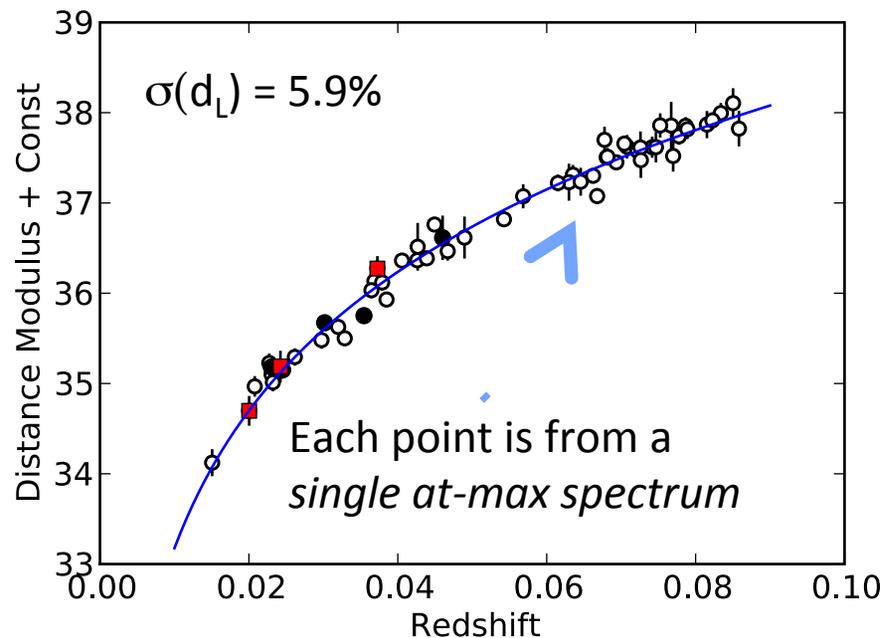
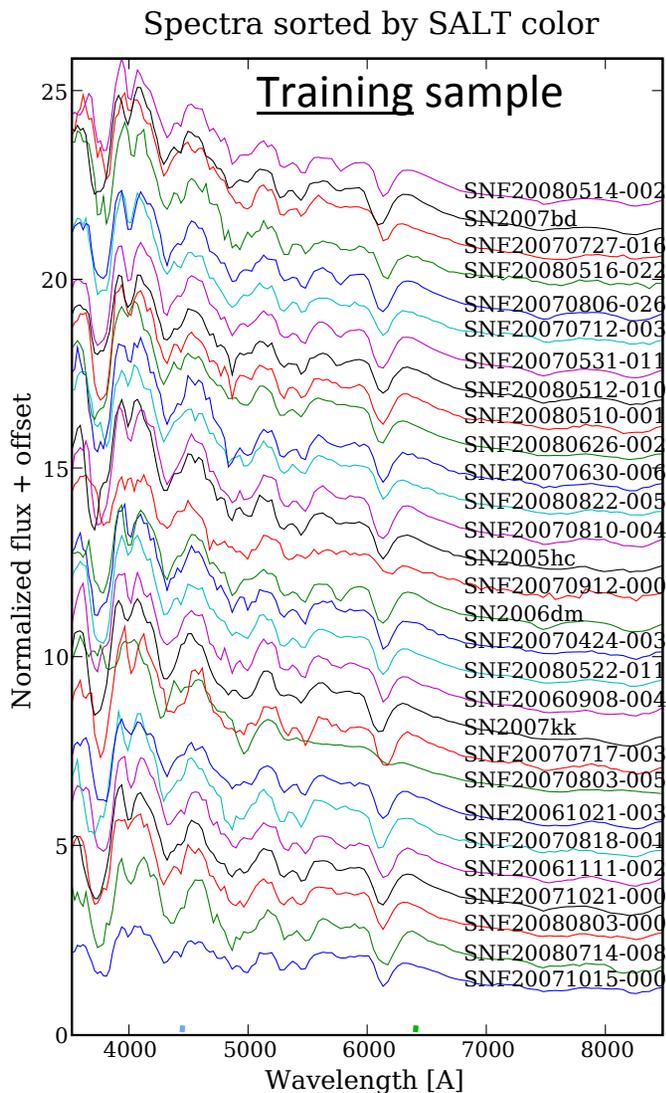
Mandel et al (2011)

# Lightcurve Standardization



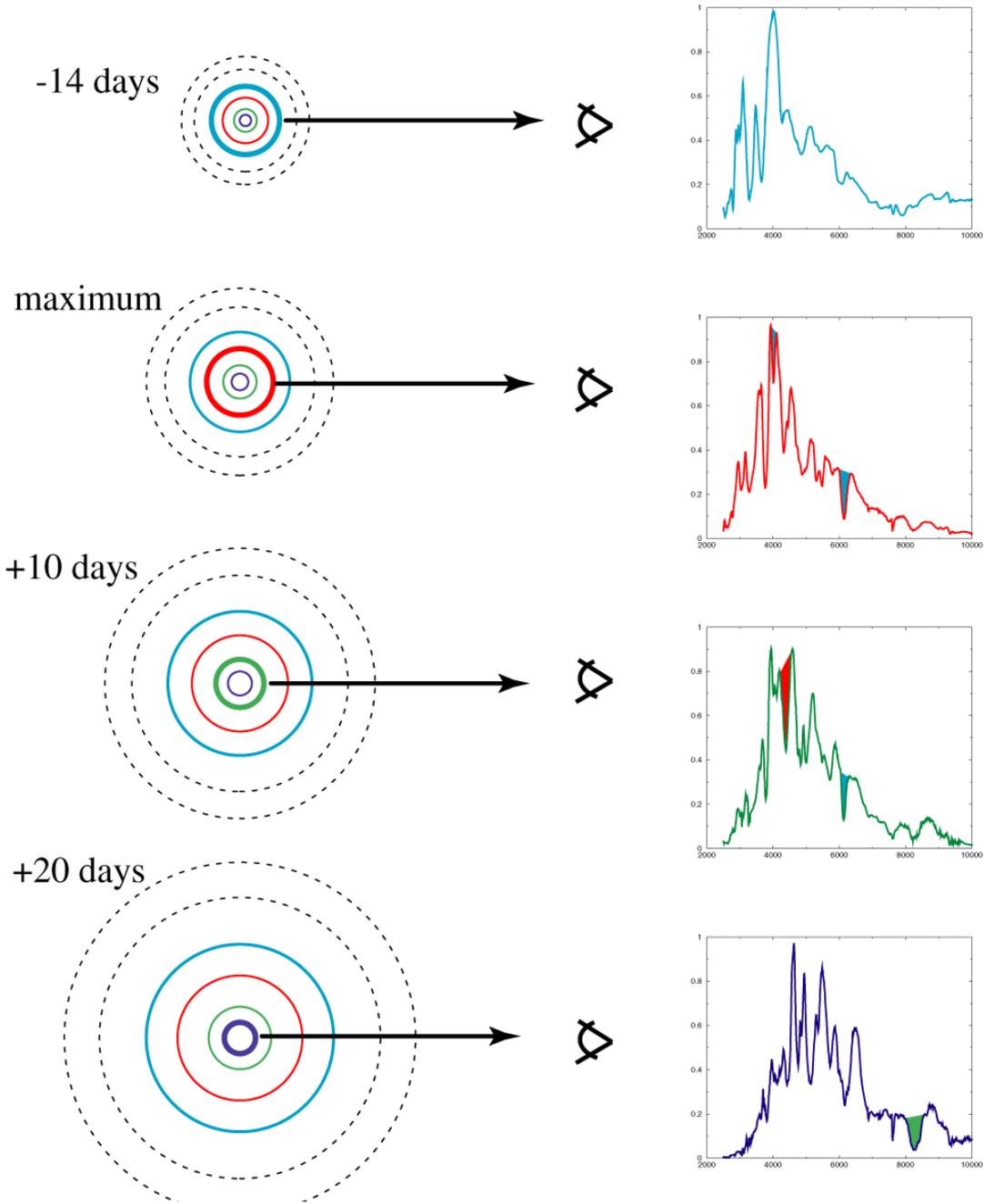
Each point is synthesized photometry from a flux-calibrated spectrum

# Spectral Flux Ratio Standardization

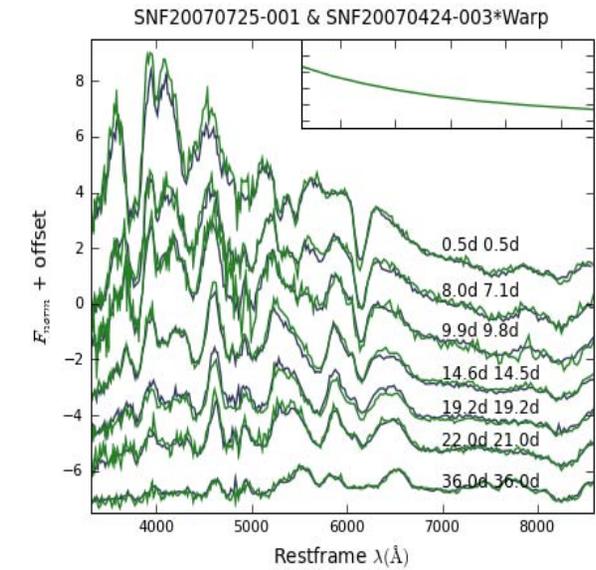
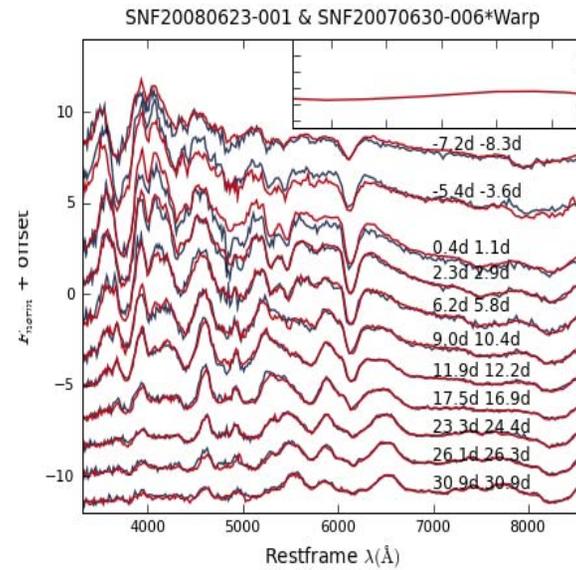
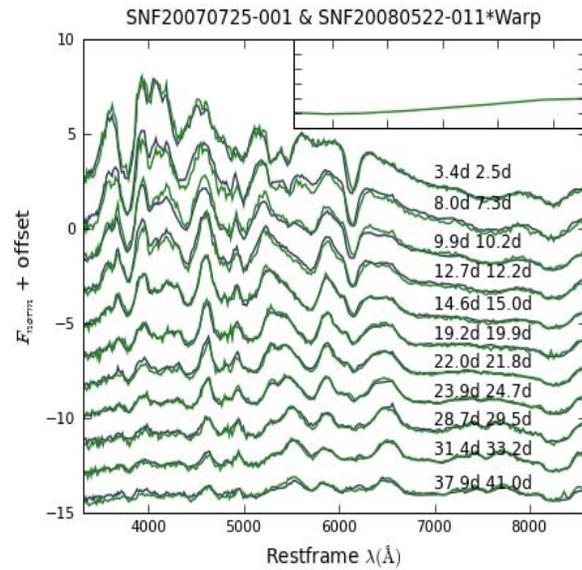
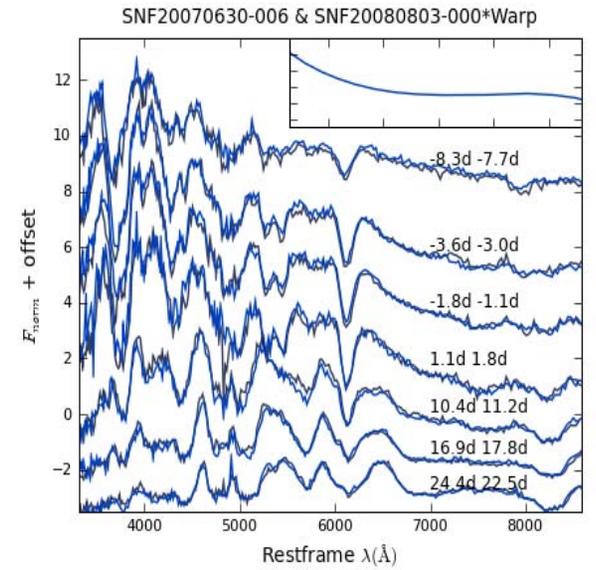
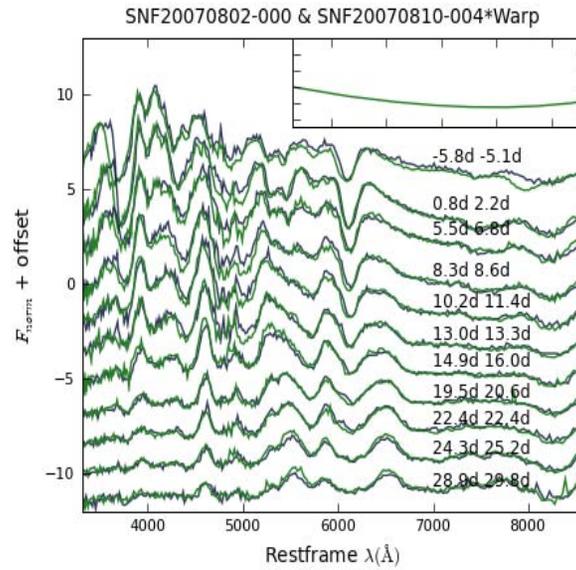
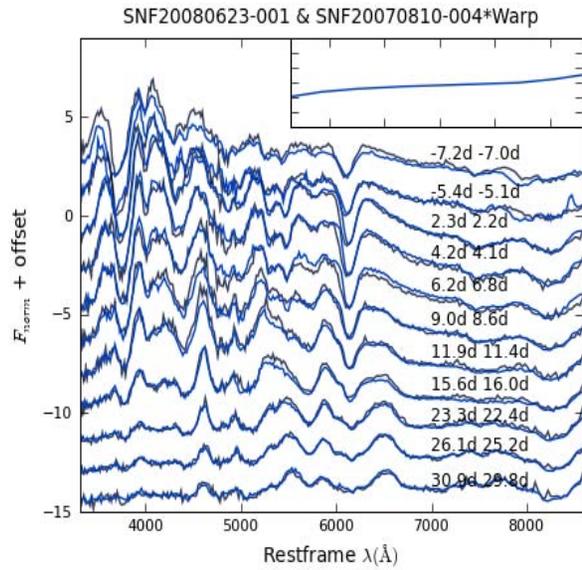


*Bailey, et al., A&A (2009)*

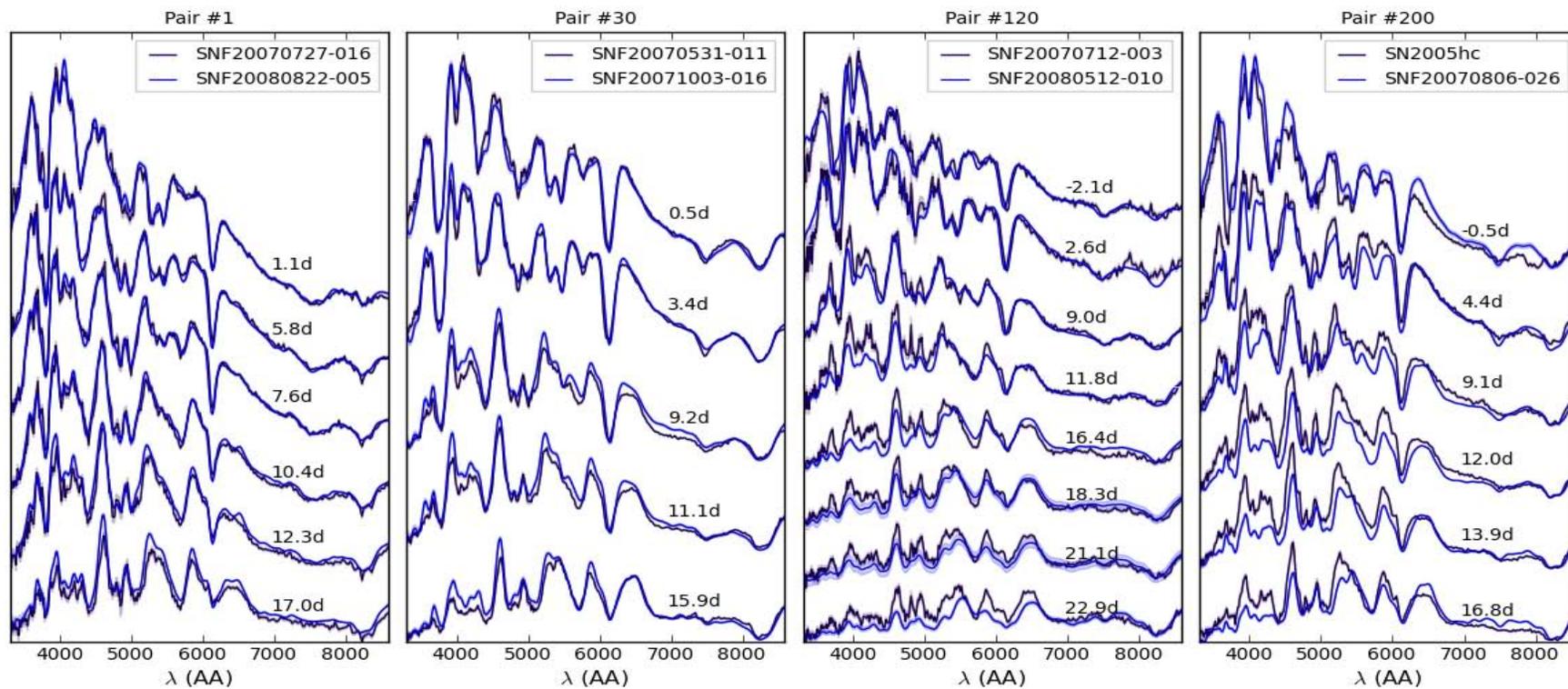
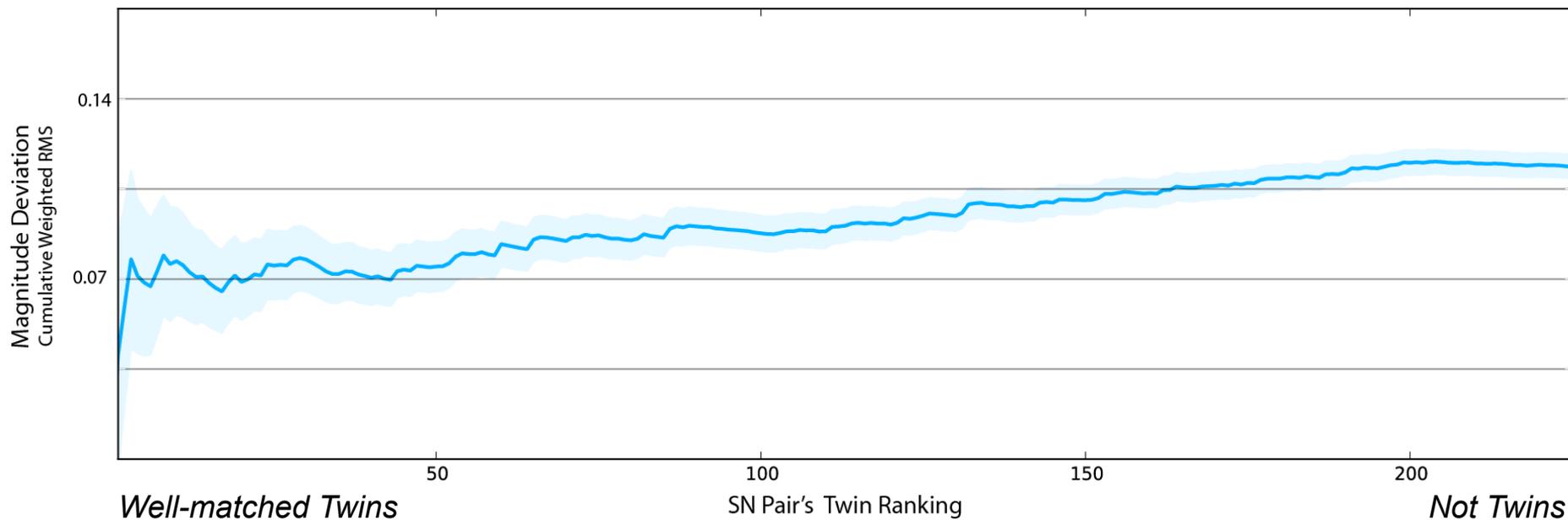
# The Time Series of Spectra is a “CAT Scan” of the Supernova

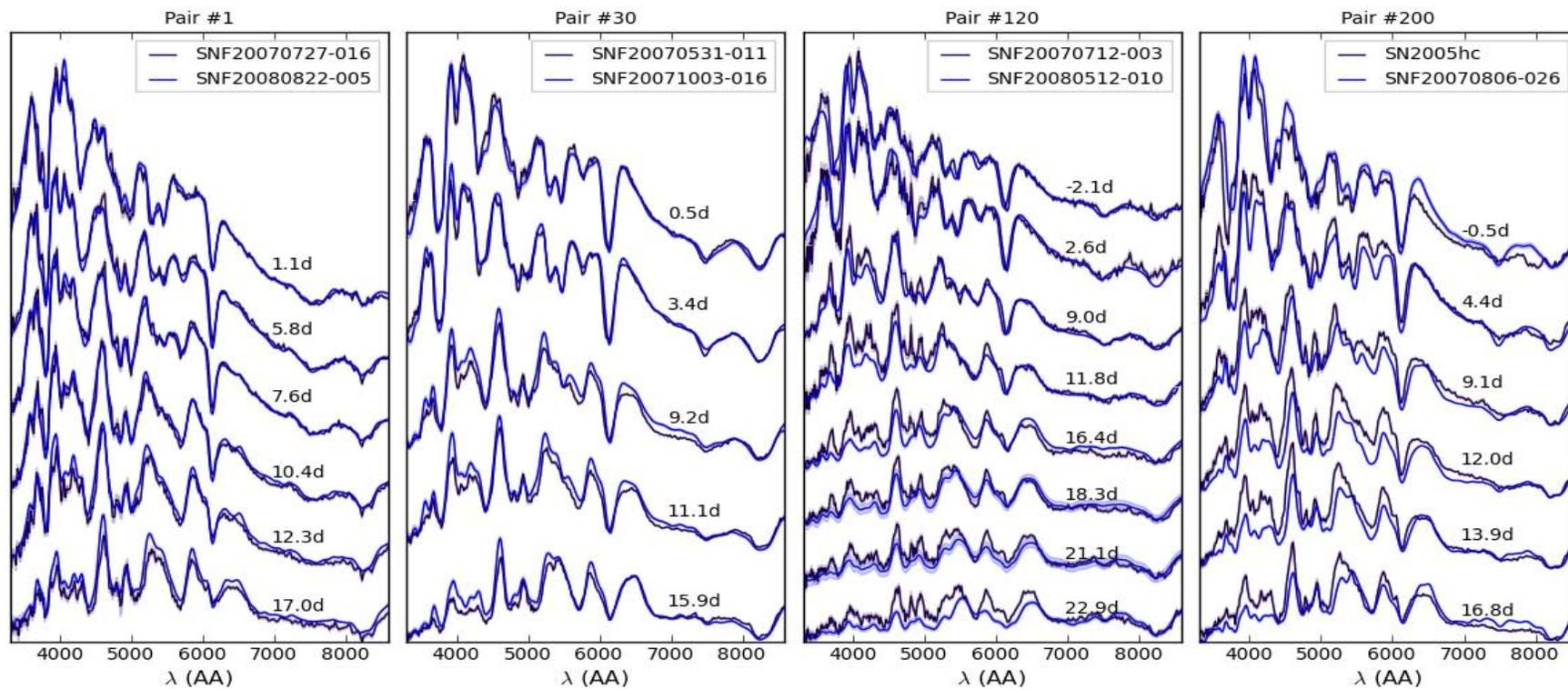


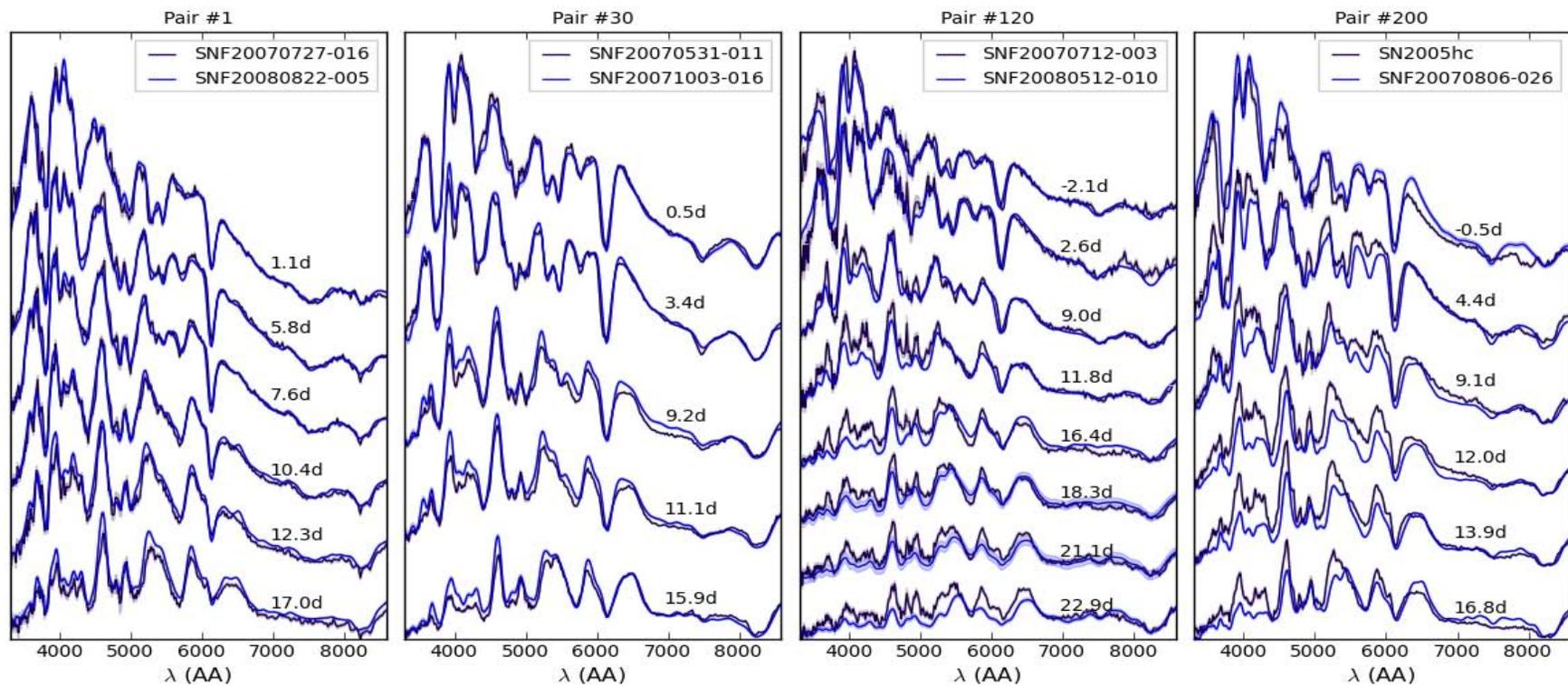
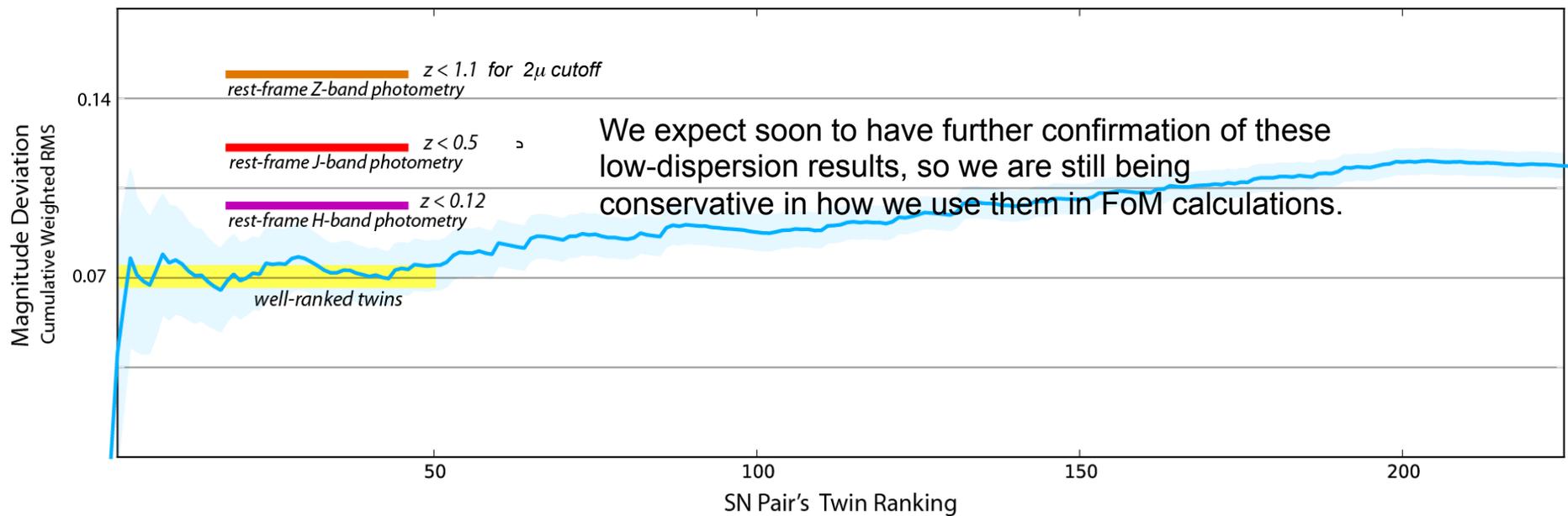
# SN Twins



SN Factory







Evolution

Low  $R_V$  &  
Intrinsic color

Filters &  
K corrections



SN



Dust  
host galaxy  
intergalactic



Gravitational  
Lensing



Atmosphere  
absorption  
emission  
blurring



Telescope



Filters



Detector  
response

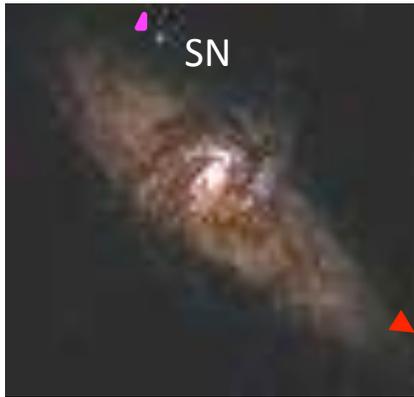


Interpretation

Calibration must be one of first design goals,  
not last.

- ' If using filters, need monochromator or IFU spectrograph.
- ' It's better to use calibrated IFU spectrograph for SN measurements.

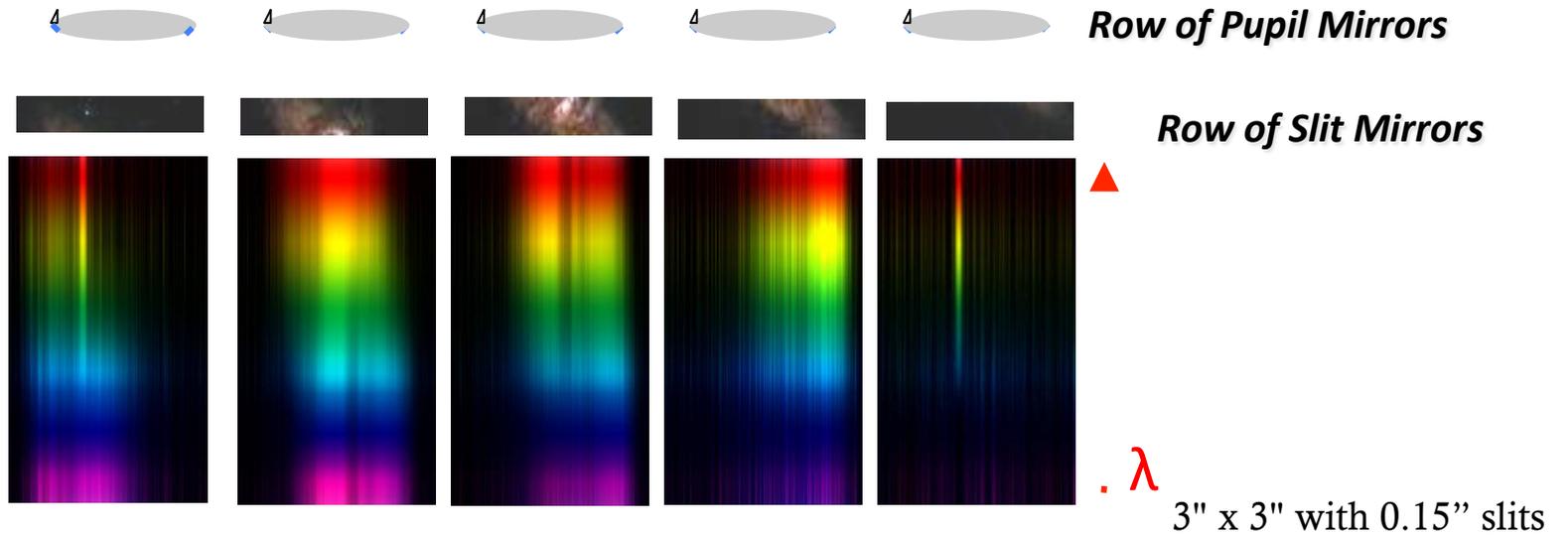
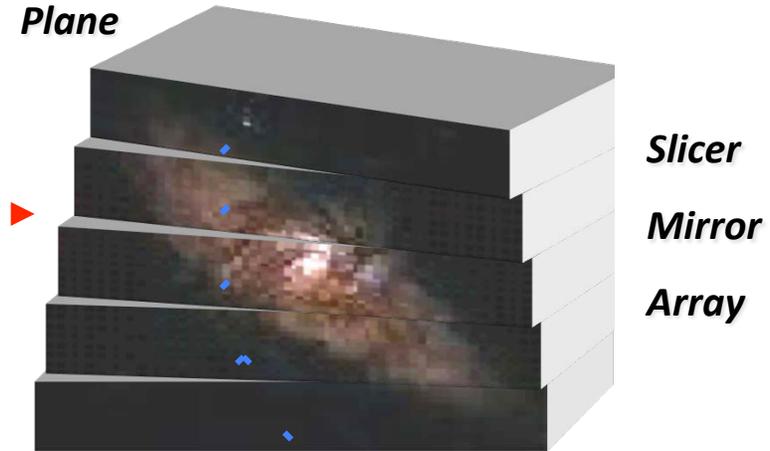
# Integral Field Spectroscopy Concept



Telescope



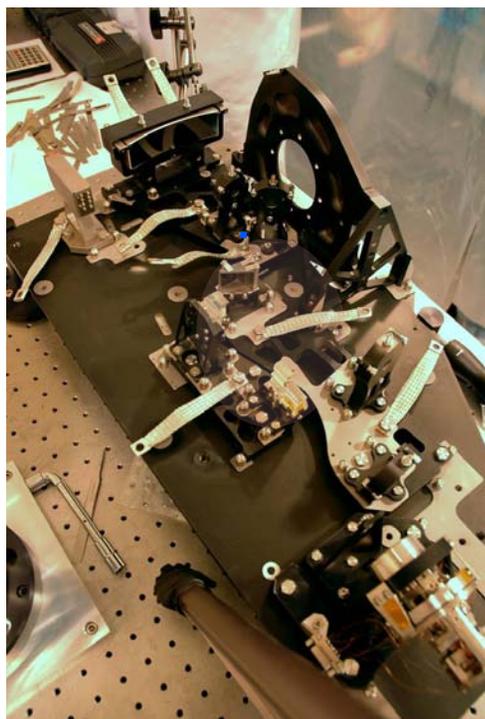
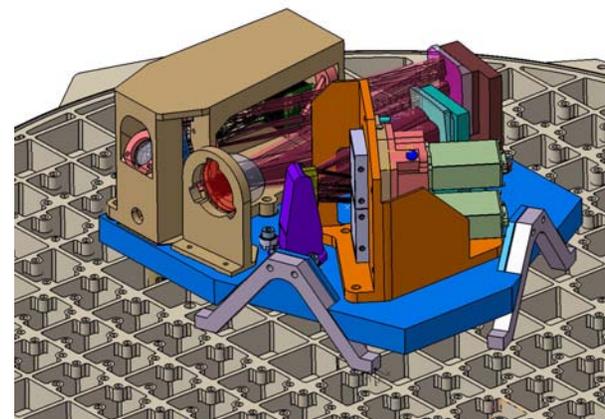
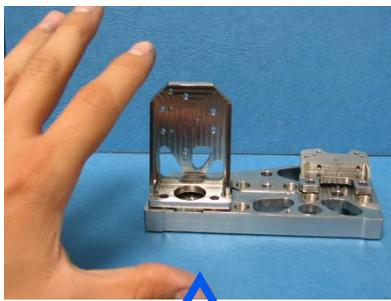
Telescope Focal  
Plane



# Prototype Space-qualified (TRL5) IFS

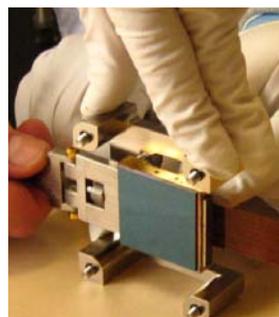
## IFS specifications:

- ❑ Mass: < 12 kg
- ❑ Size: 200 x 270 x 270 mm
- ❑ R of 70 – 200
- ❑ 0.35-1.7 micron
- ❑ Total throughput w/ OTA
  - ❑ > 55% in optical
  - ❑ > 40% in NIR



## Calibration tests:

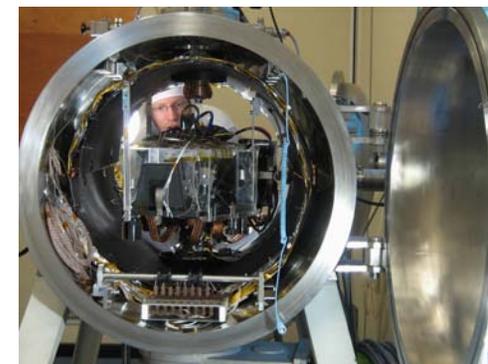
- ❑ Straylight measured to be <math>10^{-3}</math>
- ❑ Wavelength calibration at the nm level
- ❑ relative flux calibration better than 1 %



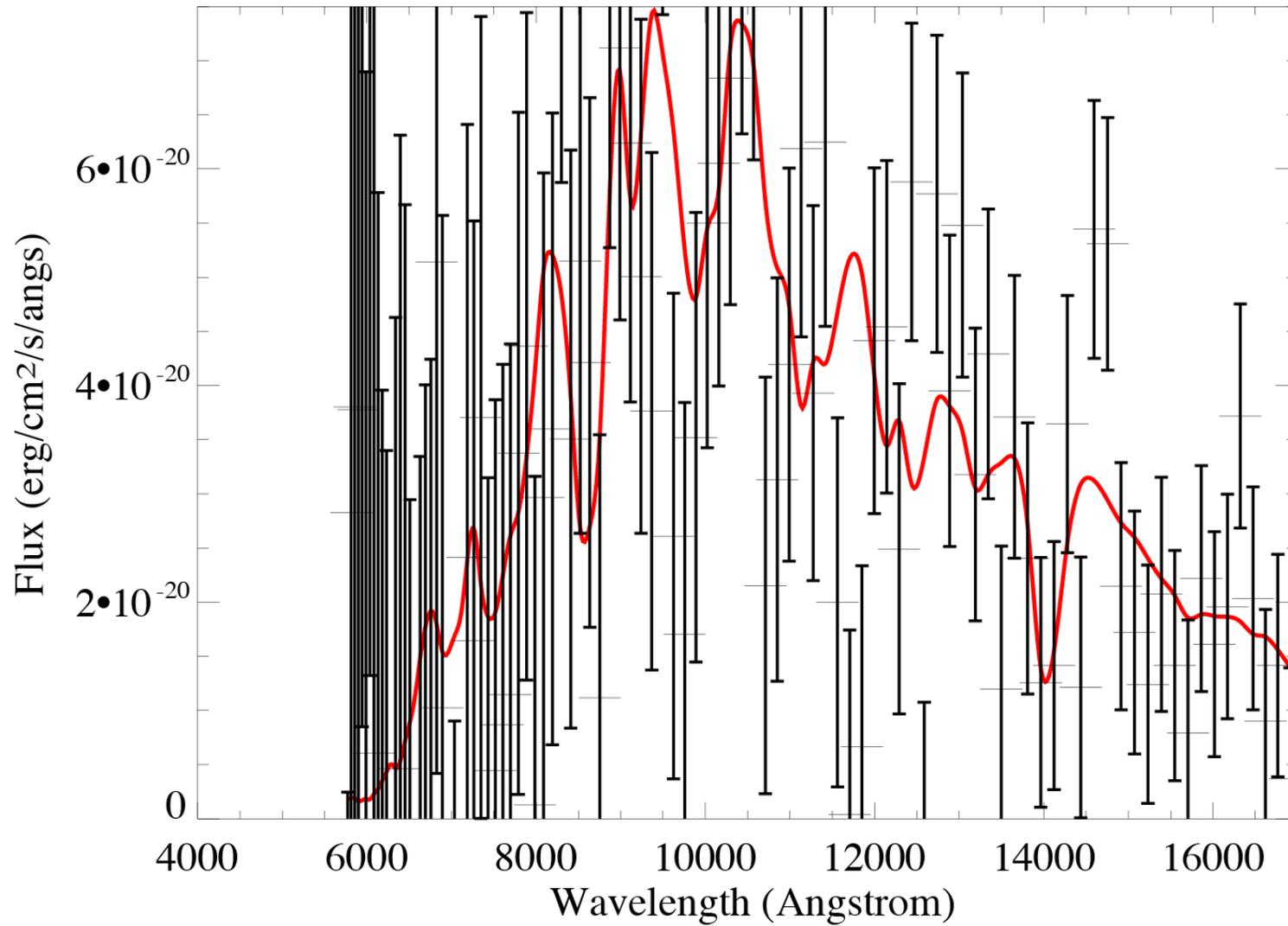
*Teledyne NIR 2k x 2k  
integrated with optics  
and readout system*

## Mechanical tests:

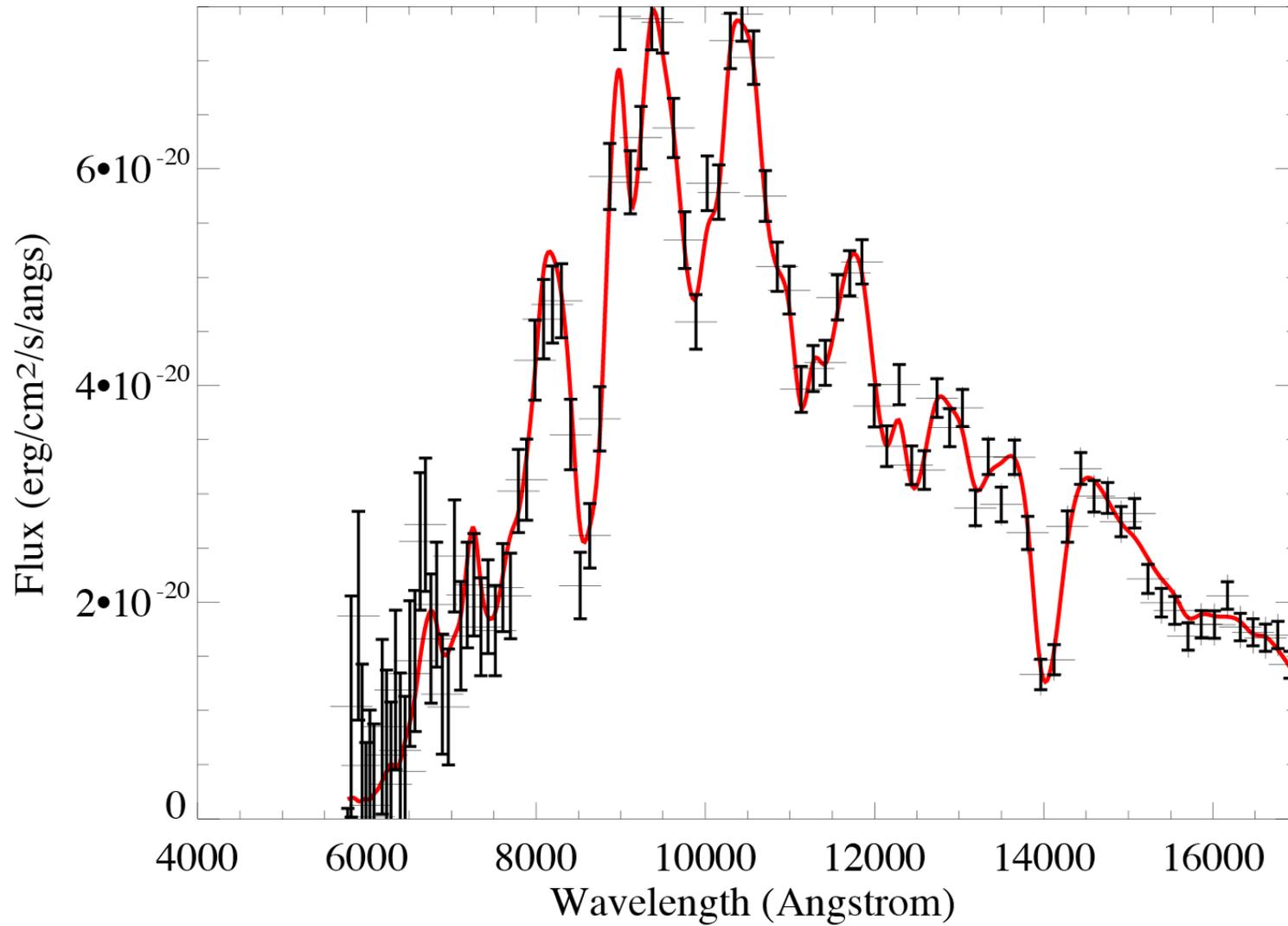
- ❑ Shake tested to JDEM spec
- ❑ Thermal cycle tested



# Signal-to-Noise of 1 SN Ia spectrum

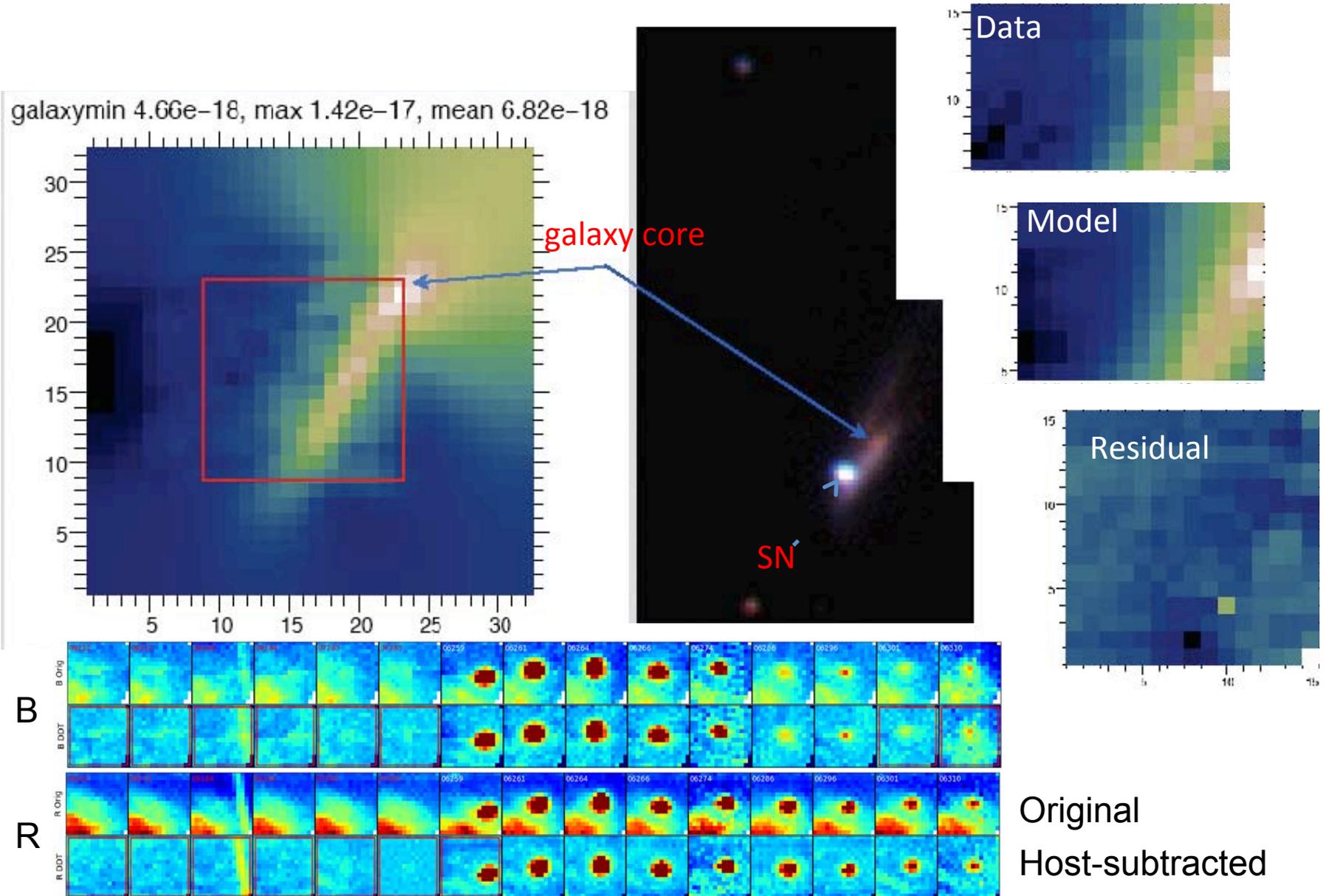


# Signal-to-Noise of 7 SN Ia spectrum



- Need spectrograph (and S/N) good enough to measure key spectral features of supernovae *after* subtracting host galaxy.

# High Fidelity Host Modeling is Key



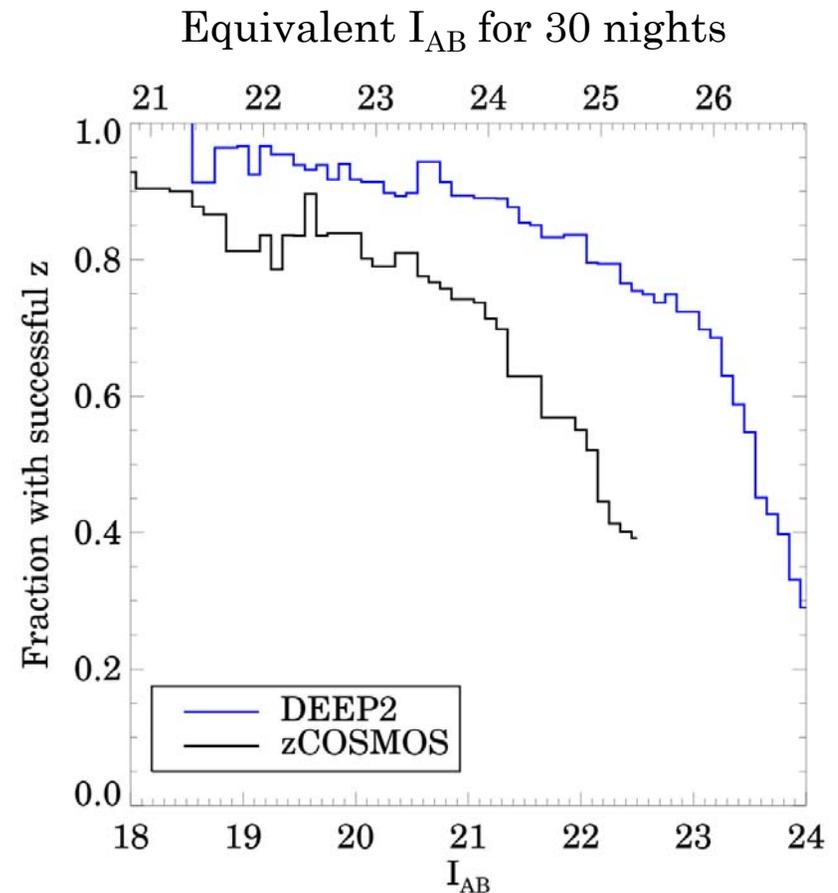
## A forgotten (difficult) requirement?

Weak Lensing needs spectroscopic calibration of photo- $z$  using unbiased sampling of random galaxies.

A possible use of IFU to obtain these calibration spectra simultaneous with SN IFU spectroscopy and with High Galactic Latitude Surveys.

# Calibrating photo-z's at LSST (or WFIRST) depth is limited by incompleteness in redshift surveys

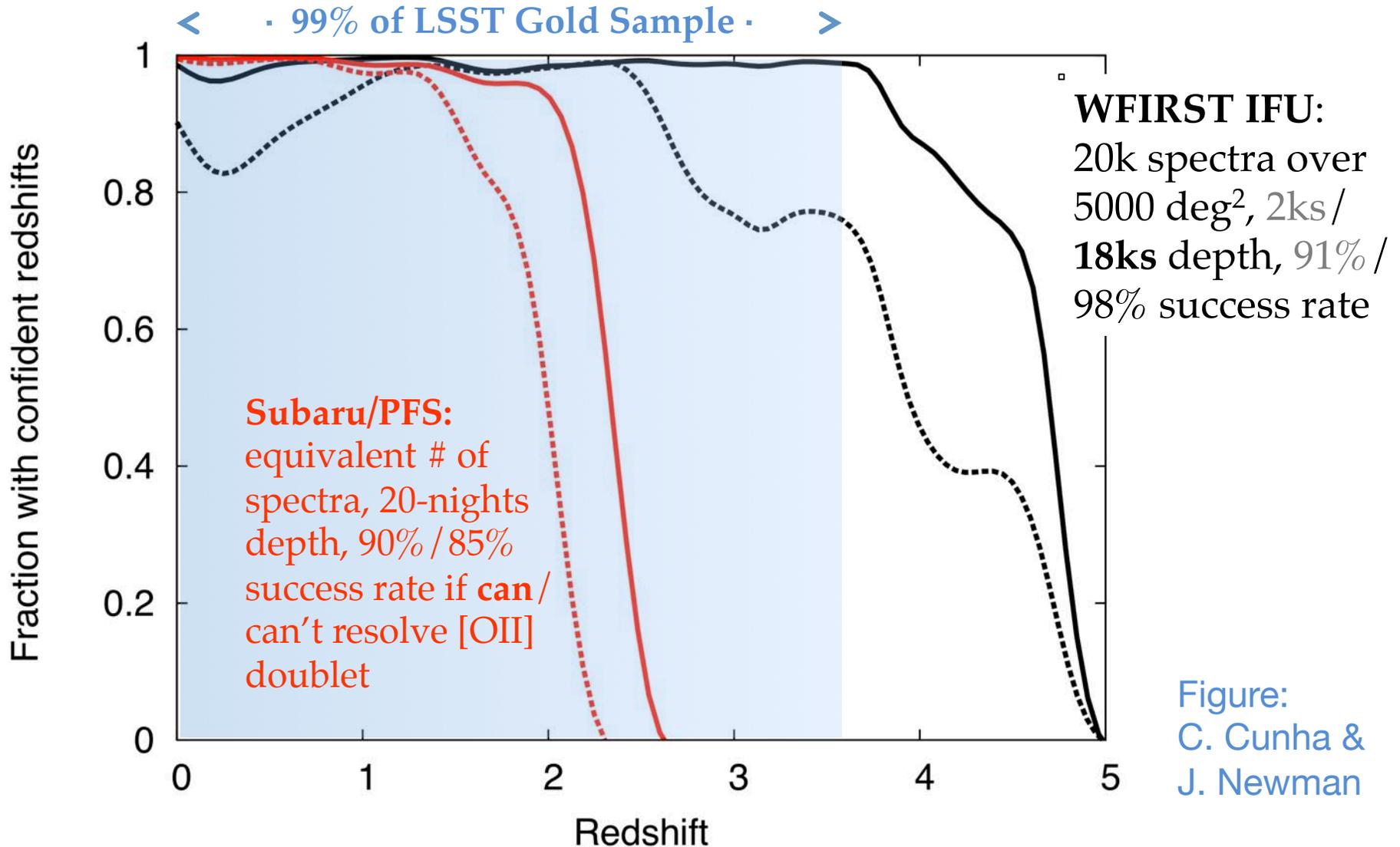
- Want training set of  $\sim 20k$  objects with very secure  $z$  measurements, spanning full parameter space & large volume
- As we are unlikely to achieve  $>99\%$  complete calibration samples, photo- $z$  calibration / redshift distributions would be determined via cross-correlation type methods (e.g. Newman 2008)
- For objects not spanned by training set, there's no accurate photo- $z$  to calibrate; want 50-75% success at least.
- Even with instruments now being built, this will be extremely difficult from the ground at  $z > 2$ , degrading DE FoM



**Redshift success rates from DEEP2 (Newman et al. 2012), zCOSMOS (Lilly et al. 2009)**

# LSST WL FoM is >2x larger if can train at $z > 2$ with IFU

A bigger issue for WFIRST WL:  $H$ -limited sample skews to higher  $z$ !



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A bigger issue for WFIRST WL:  $H$ -limited sample skews to higher  $z$ !

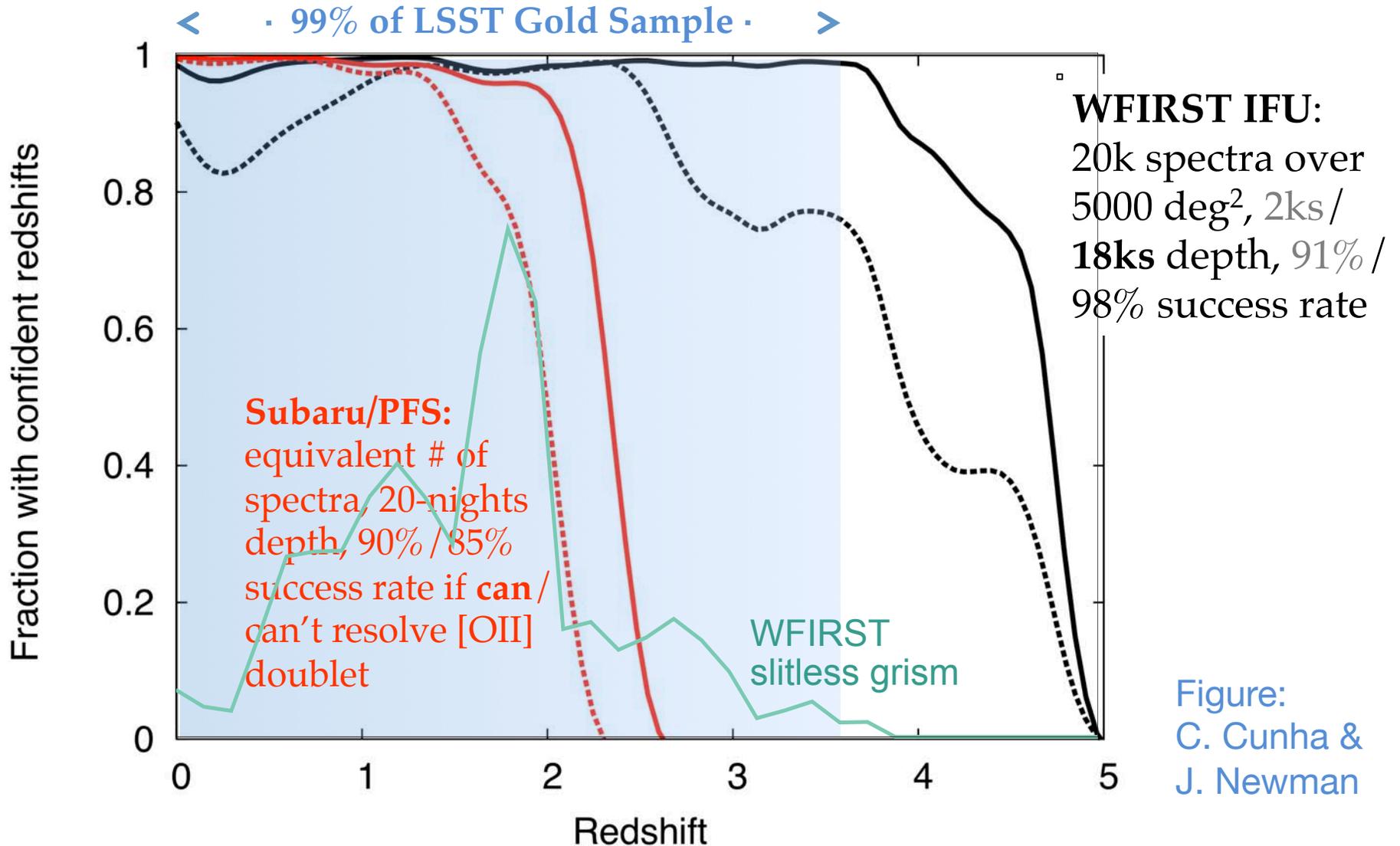


Figure:  
C. Cunha &  
J. Newman



## Design Rule

Design as if you know that the answer will be a very small, but statistically clear deviation from  $(w_0 = -1, w_a = 0)$ .

Otherwise DE measurement not worth  $\$10^9$ .

Backup Slides

## Derivation of formula to estimate Exp time

- Signal =  $st$
- Background =  $n_{\text{pix}}(Z+D+r^2/t) t$
- $\sigma_{\text{stat}} = (st)^{1/2}$
- $\sigma_{\text{bkgrd}} = [n_{\text{pix}}(Z+D+r^2/t) t]^{1/2}$
- $\sigma_{\text{tot}} = (\sigma_{\text{stat}}^2 + \sigma_{\text{bkgrd}}^2)^{1/2}$
- $S/N = \text{signal}/\sigma_{\text{tot}} = (st)/[st + n_{\text{pix}}(Z+D+r^2/t) t]^{1/2}$
- $t = [(S/N)/s]^2 [s + n_{\text{pix}}(Z+D+r^2/t)] \text{ sec}$

## Silicon II Spectral Feature

In Observer Frame	SNe rest Frame	Z=0.5	Z=1.0	Z=1.5
$\lambda$ central	6100	9150	12200	15250
FWHM	160	240	320	400
FW at base	320	480	640	800
Å per pixel	41	61	82	102
FWHM in pixels	3.9	3.9	3.9	3.9
FW at base in pixels	7.8	7.8	7.8	7.8
S/N per pixel coadded sp*	2.1	2.1	2.1	2.1
S/N per pixel single sp**	0.7	0.7	0.7	0.7

\*Signal to noise per pixel in co-added spectra to get a S/N = 5 for the Si feature. Use 6 pixels, so  $5/\sqrt{6} = 2.1$

\*\*Assume that S/N in a co-added spectrum (i.e.co-add all spectra in the lightcurve) is 3 times the S/N in a single spectrum

**Conclusion: Need S/N per pixel = 0.7 for single spectra**

# Survey Areas

- We want square areas so we can continuously monitor it as we go around a corner every three month with a 90 degree turn of the detector plane
- For DRM A assume 18 H4RG detectors are arranged in a 6 x 3 pattern so the imager is not square
- For example
  - Two imager footprints make a 6x6 sensor square
  - 8 imager footprints make a 12x12 square
  - etc

## Square Survey Areas for DRM A

Pattern	Sensors	Area(sq degrees)	No of shots
1 W x 2 H	6 x 6	0.56	2
2 W x 4 H	12 x 12	2.24	8
3 W x 6 H	18 x 18	5.04	18
4 w x 8 H	24 x 24	8.96	32
5 W x 10 H	30 x 30	14.00	50
6 W x 12 H	36 x 36	20.16	72
7 W x 14 H	42 x 42	27.44	98

DRM A has 18 H4RG detectors with 10 micron pixels

The image plane is 6 detectors Wide and 3 detectors High

A pattern of 2W x 4 H is 8 image planes arranged 2 in the W direction and 4 in the H direction

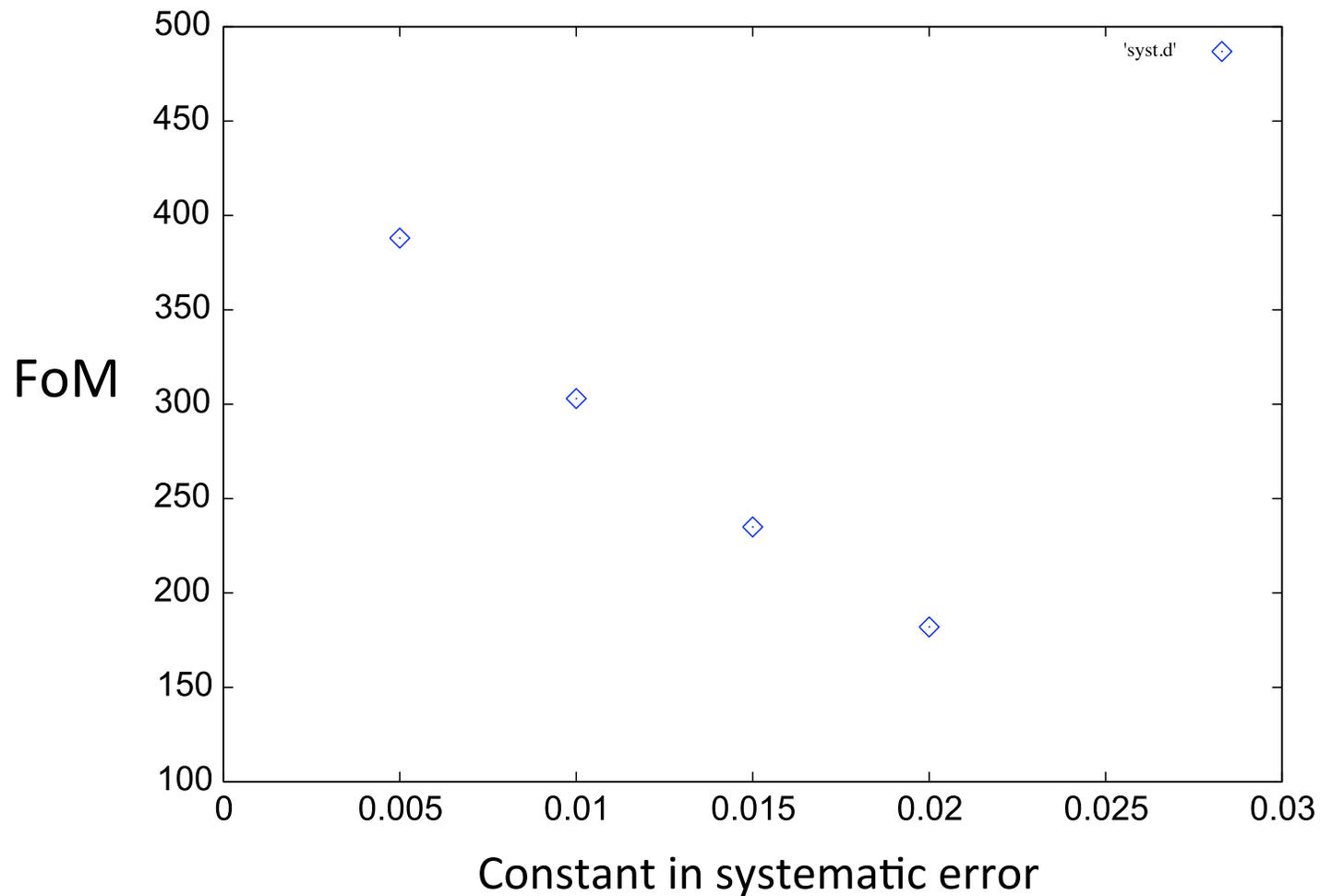
No of shots is number of exposures to cover the area in a filter

We should stick with these patterns for best efficiency

# FoM dependence on Systematic Error

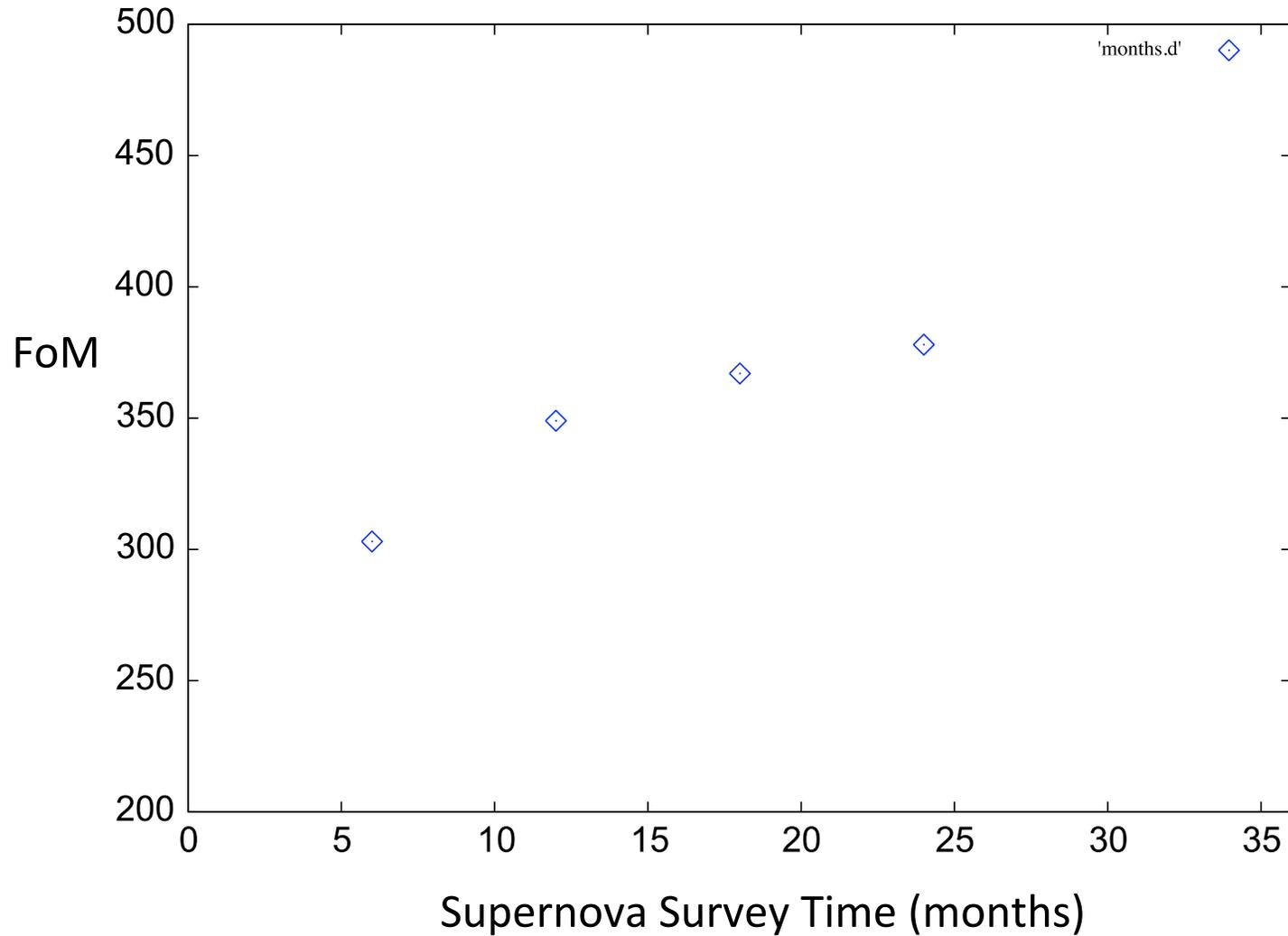
IFU Deep Survey with spectroscopic lightcurves

$$\sigma_{\text{sys}} = \text{constant} \times (1+z)/1.8$$



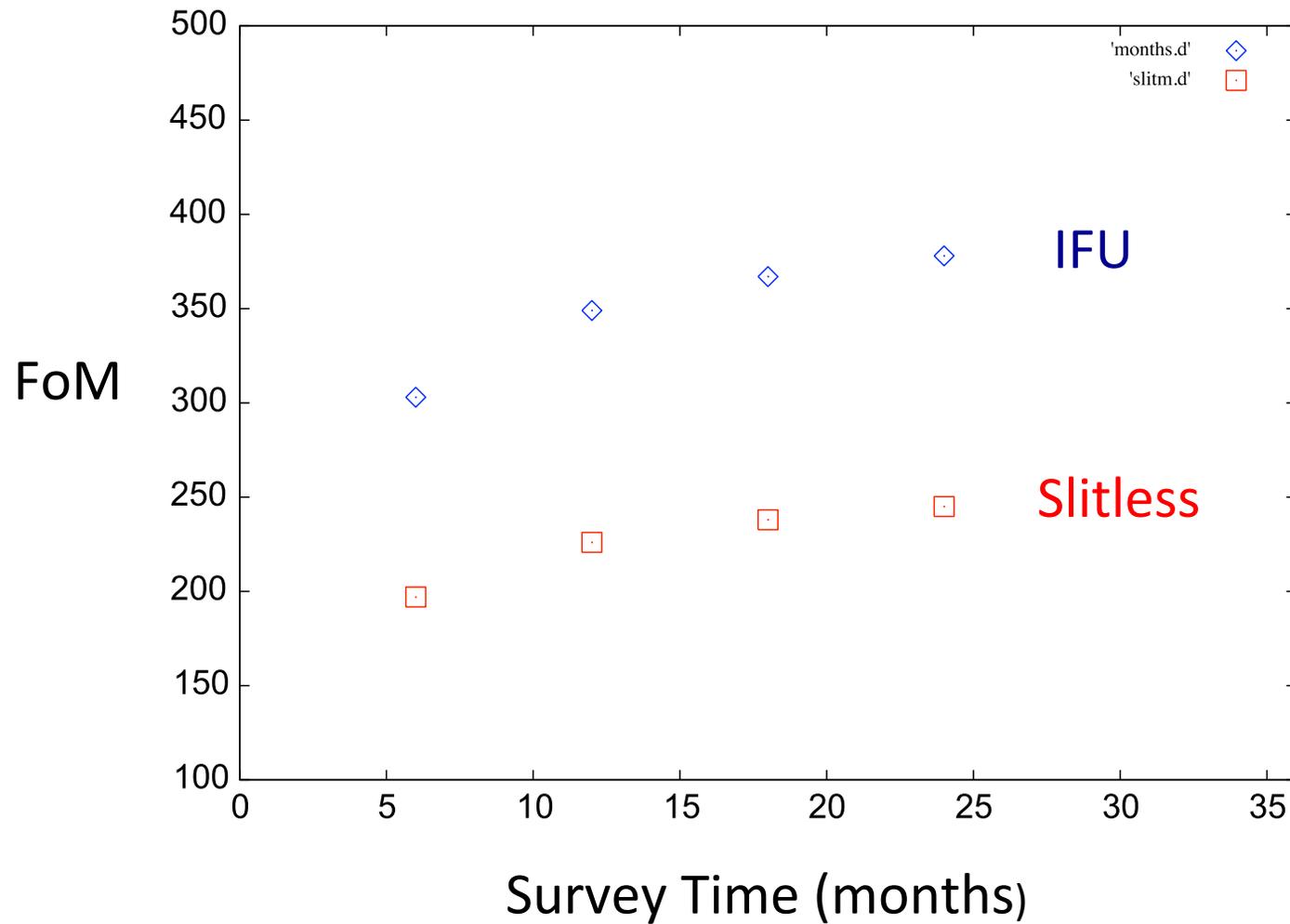
# FoM dependence on Supernova Survey Time

IFU Deep Survey with spectroscopic lightcurves



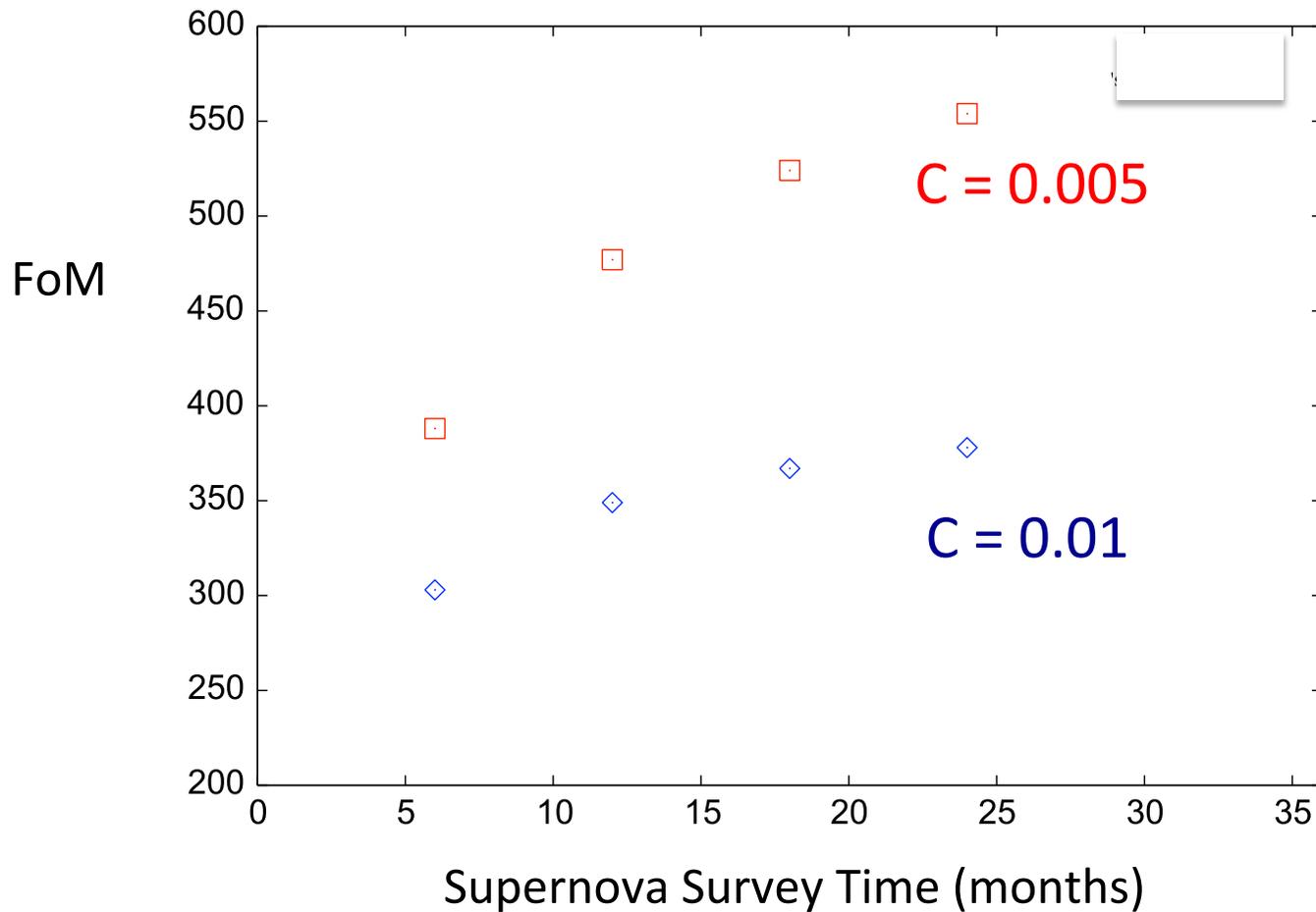
# FoM dependence on Supernova Survey Time

## Lightcurves from Spectroscopy



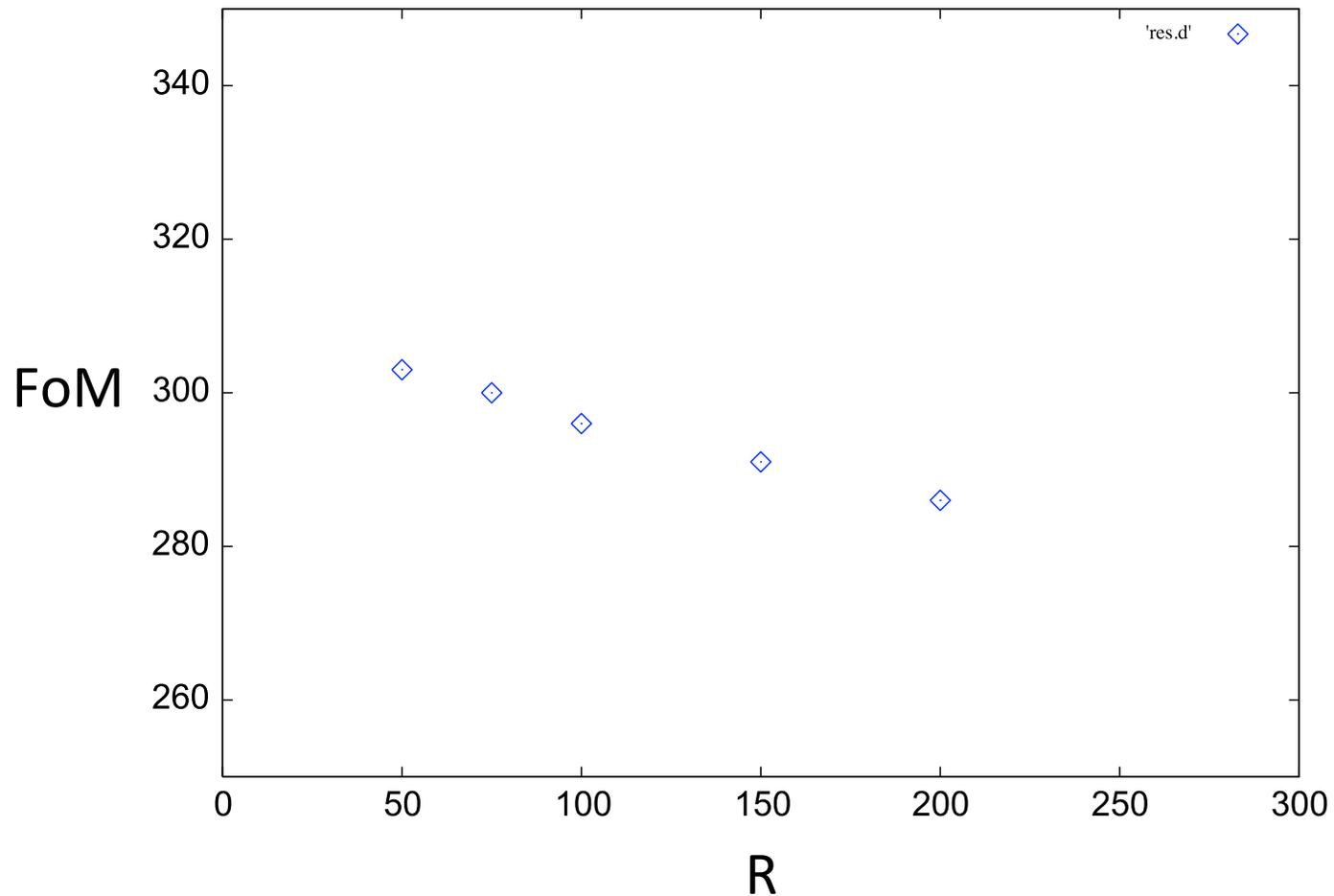
# FoM dependence on Supernova Survey Time

IFU Deep Survey with spectroscopic lightcurves  
Systematic error =  $c \cdot (1+z)/1.8$



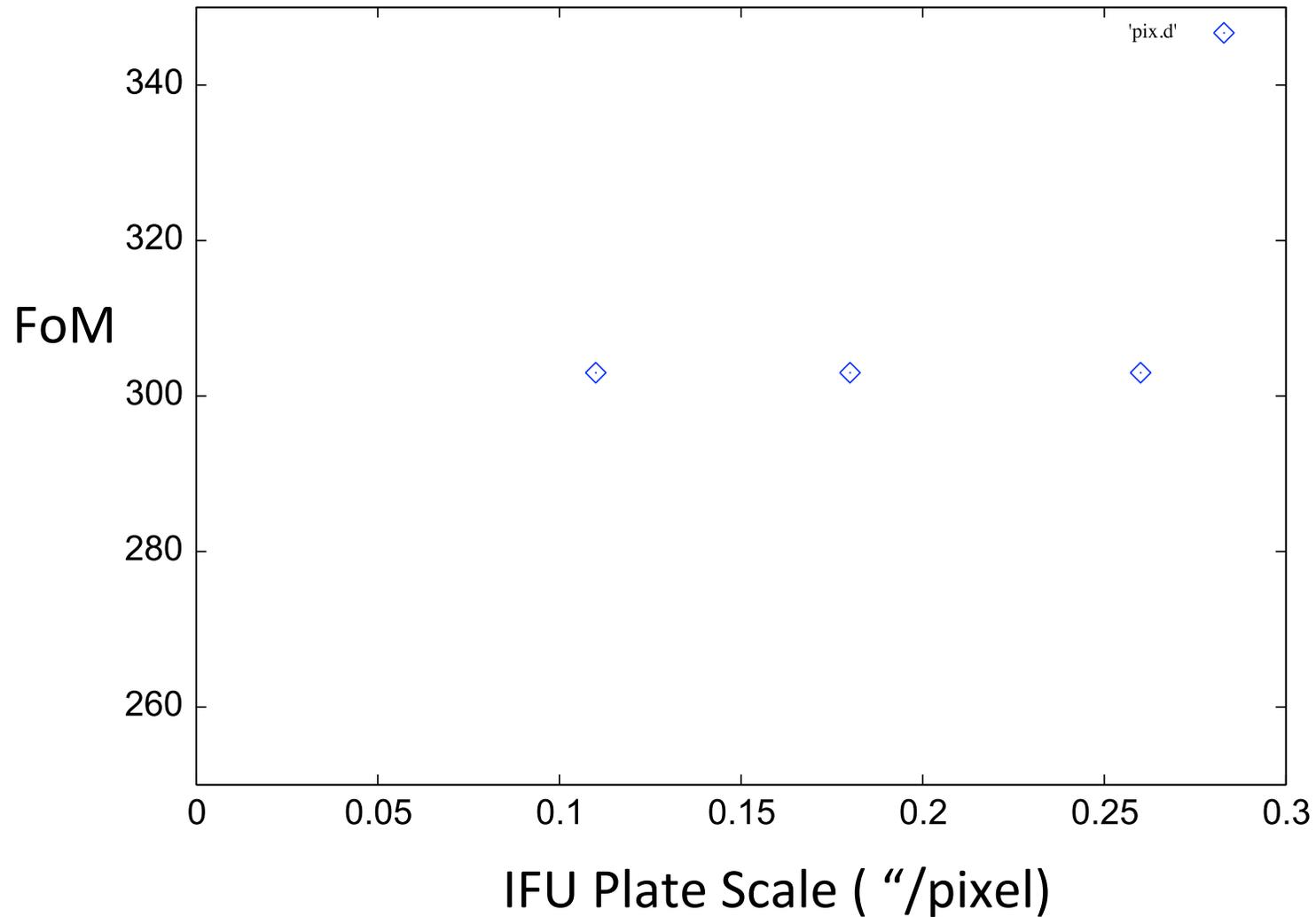
# FoM dependence on IFU Resolution

IFU Deep Survey with spectroscopic lightcurves



# FoM dependence on IFU Plate Scale

IFU Deep Survey with spectroscopic lightcurves





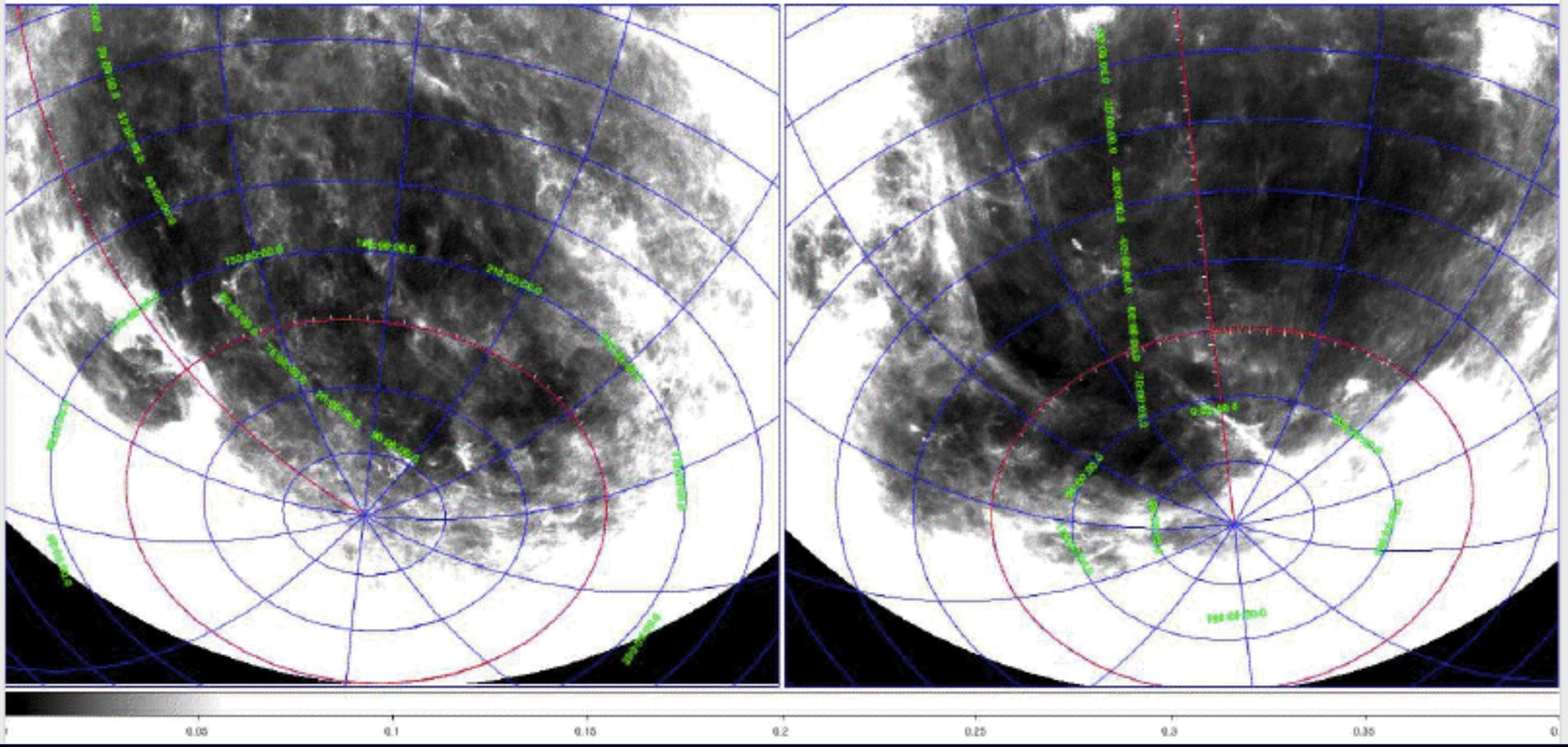
# Dust Map – Ecliptic Coordinates

- Galactic Dust affects observed magnitude
- Uncertainties in dust correction affect Hubble Diagram

North

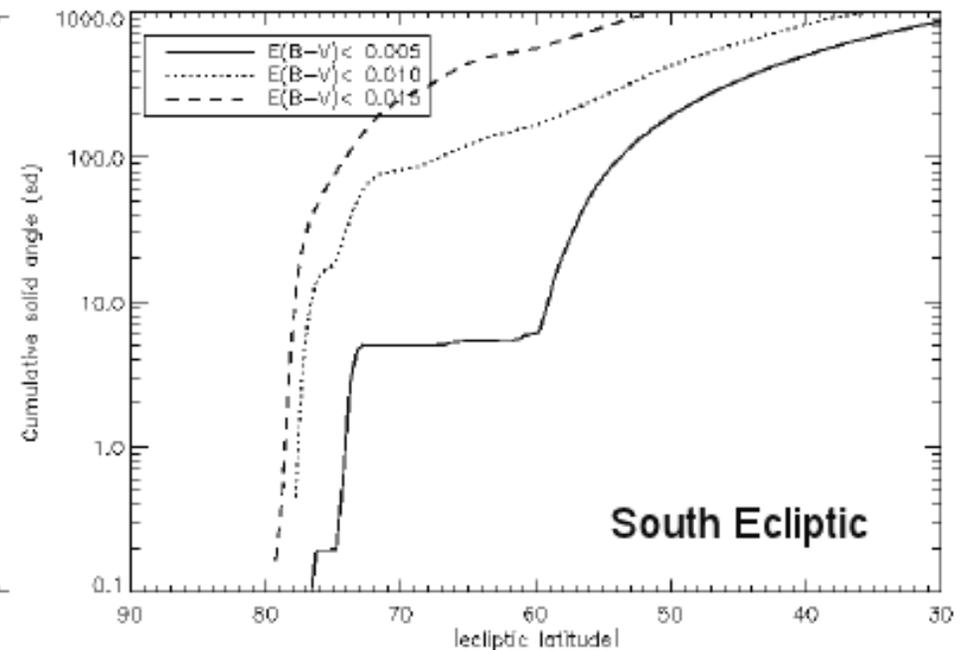
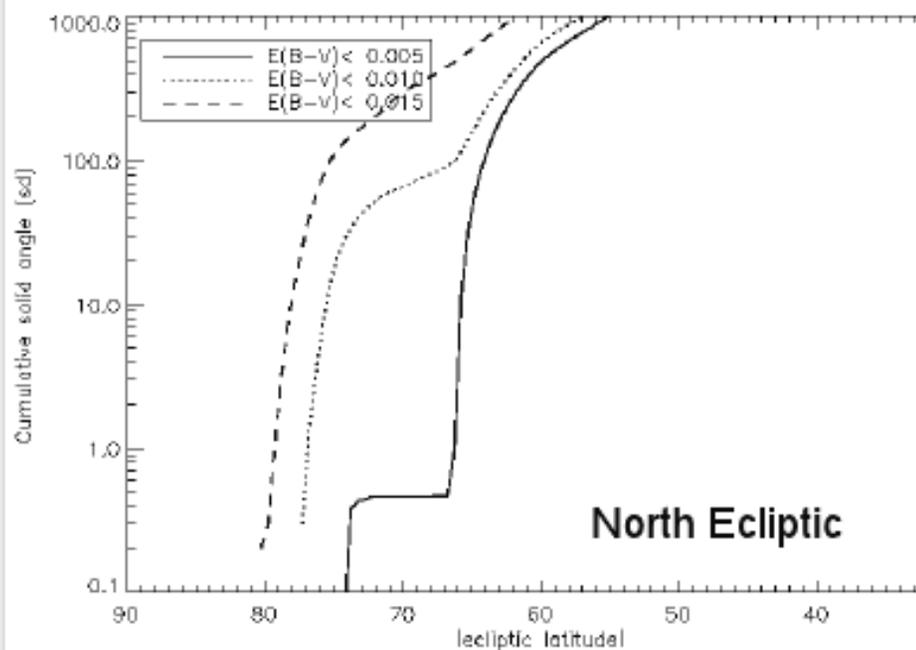
South

E(B-V) maps of SFD



# Galactic Dust vs Ecliptic Latitude

- Plots of cumulative solid angle less than  $E(B-V)$  thresholds as a function of ecliptic latitude





# What the Reports Said

## JDEM SCG:

The RM can accommodate an Integral Field Unit (IFU) spectrograph, such as the one that has been prototyped and space-qualified for JDEM by the LAM/Marseille group. The IFU spectrograph was the subject of a recent two-week NASA/Goddard Mission Design Lab (MDL) study and has had substantial oversight from GSFC. Such a spectrograph provides  $R=75\text{--}100$  visible-to-infrared spectrophotometry with 100% fill factor for every pixel in a 3 arcseconds by 6 arcseconds FOV at a pixel scale of 0.15 arcseconds per pixel. A complete IFU has been designed to fit within a small 15x15x30 cm volume, with a weight of <12 kg.

In addition to the speed advantages, the efficiency of the IFU spectrophotometry can make possible detailed spectroscopic characterizations of the SNe that help constrain the SN distance measurement systematics (e.g. due to evolution of SN properties and dust). In particular, the measurements of spectral feature ratios and line velocities require much higher signal-to-noise spectra than the simple identification of Type Ia SNe and redshift determination.

4) The IFU exposure times can be tuned to the apparent magnitude of each SN, whereas for multiplex observations with a slitless prism all exposures must reach the maximum target redshift for any given tier (in, e.g., a "layer cake" observing strategy). Since the exposure times increase extremely steeply with redshift ( $\sim[1+z]^6$ ), multiplexing is therefore a minor effect in practice. In fact, with  $t_{\text{exp}} \sim [1+z]^6$ , most of the spectroscopy observing time goes into the very highest redshifts, where there are few ( $\sim 2$ ) SNe contributing significant signal simultaneously in any field. 5) An IFU spectrograph supports an adaptable SN program that can respond to new knowledge and be tuned to emphasize different SN epochs and different redshift distributions, while avoiding bias against faint SNe.

**Wide-Field InfraRed Survey Telescope  
WFIRST  
Final Report**

**Science Definition Team**

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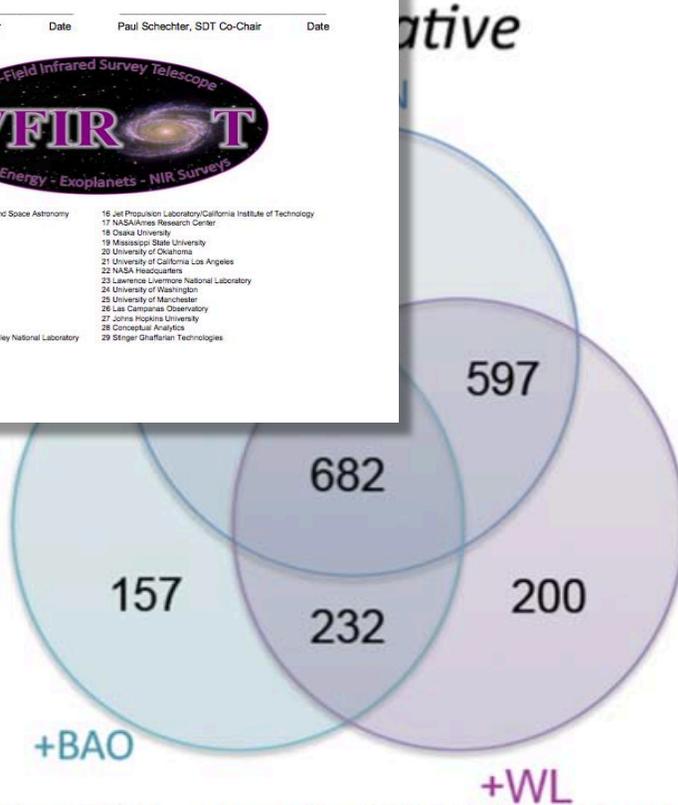
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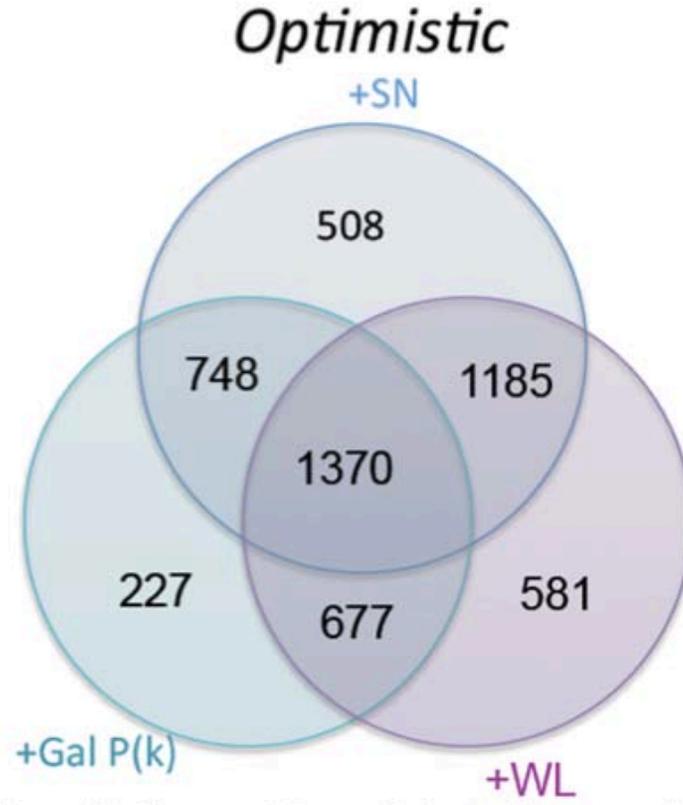
James Green, SDT-Co-Chair      Date      Paul Schechter, SDT Co-Chair      Date



- 1 University of Colorado/Center for Astrophysics and Space Astronomy
- 2 Massachusetts Institute of Technology
- 3 Yale University
- 4 Cornell University
- 5 University of Notre Dame
- 6 Space Telescope Science Institute
- 7 University of Nottingham
- 8 Michigan State University
- 9 University of Arizona
- 10 Ohio State University
- 11 California Institute of Technology
- 12 National Optical Astronomy Observatory
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- 25 University of Manchester
- 26 Las Campanas Observatory
- 27 Johns Hopkins University
- 28 Conceptual Analytics
- 29 Stringer Ghaffarian Technologies



**Figure 29: Forecasts of the DETF FoM for different combinations of the DRM1 WFIRST probes. All forecasts in-**



**Figure 30: Same as Figure 29, but using our optimistic assumptions for SN and WL systematics and using full P(k) information from the galaxy redshift survey.**